National Incinerator Testing and Evaluation Program: Environmental Characterization of Mass Burning Incinerator Technology at Quebec City

Summary Report

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June 1988

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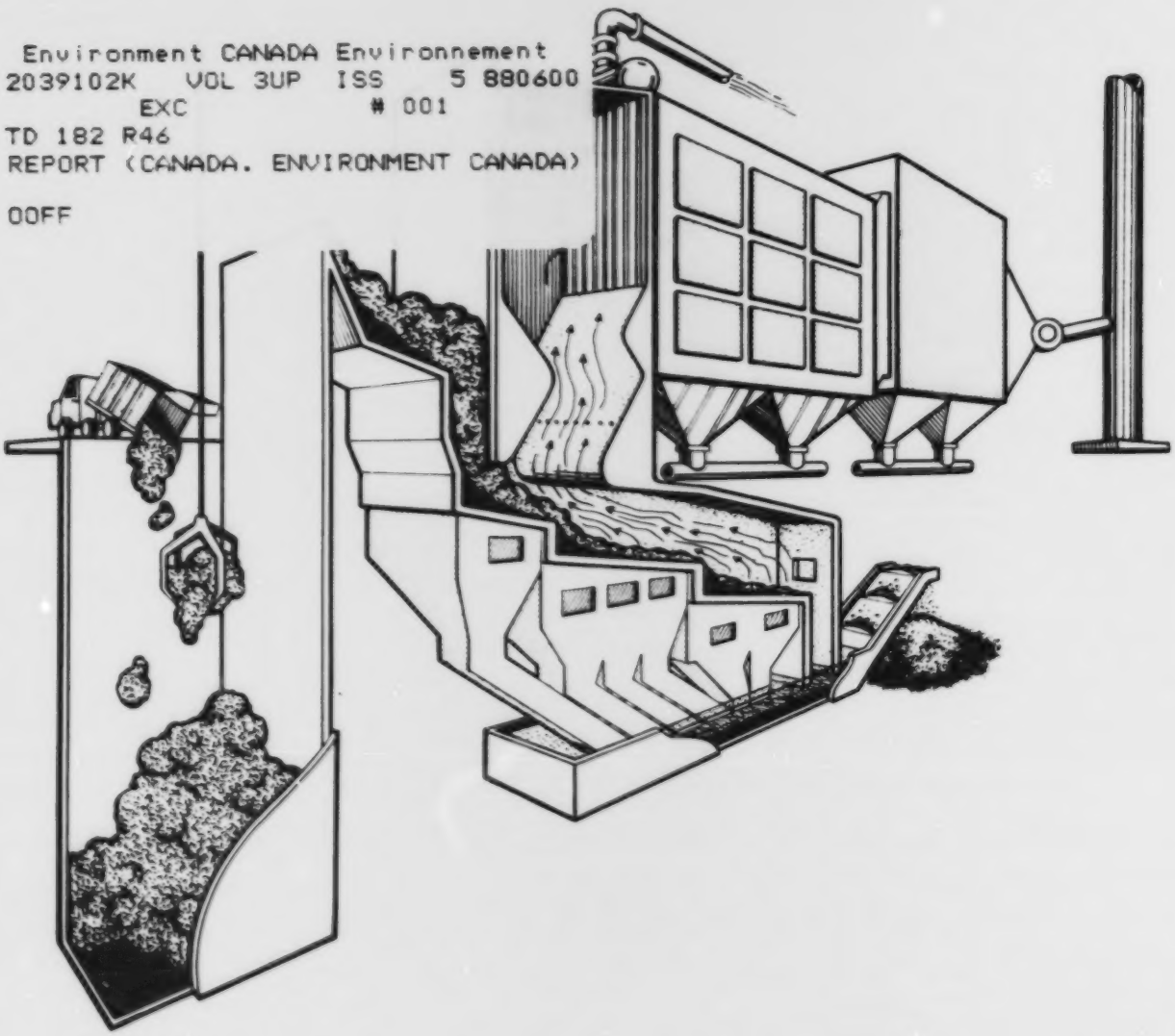

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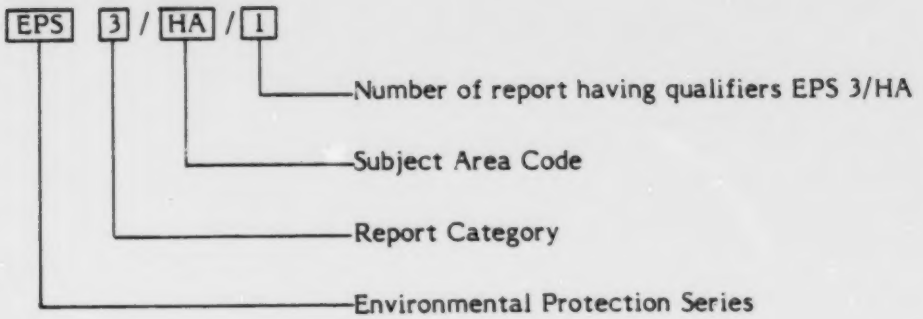
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NATIONAL INCINERATOR TESTING AND EVALUATION PROGRAM: ENVIRONMENTAL CHARACTERIZATION OF MASS BURNING INCINERATOR TECHNOLOGY AT QUEBEC CITY

Summary Report

Environmental Protection
Conservation and Protection
Environment Canada

Report EPS 3/UP/5
June 1988

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ABSTRACT

The environmental characterization of mass burning incinerator technology is the second of three incinerator technologies being tested under Environment Canada's National Incinerator Testing and Evaluation Program. The main objective of this program is to define the optimum design and operating conditions to minimize emissions of concern. The facility tested is located in Quebec City, and was built in 1974. For the testing program, one of the incinerator furnaces was modified to a "state-of-the-art" unit at a cost exceeding two million dollars.

The new furnace design was evaluated during a three-month period. Based on 19 characterization tests, five performance conditions were selected for extensive testing and 13 performance tests were successfully completed. All incoming wastes and ash residues were weighed, sampled and analyzed. Key incinerator operating variables, such as refuse feed rate, furnace radiation chamber temperatures, undergrate/overfire air distribution and other process parameters, were monitored by an extensive computer network system on a "real time" basis. A wide range of analyses was carried out on exhaust gas emissions and all the ash discharges, including analyses for dioxins, furans, polychlorinated biphenyls, chlorophenols, chlorobenzenes, polycyclic aromatic hydrocarbons, over 30 heavy metals, and acid gases.

Under good operating conditions, dioxin emissions from the modified furnace were 40 to 100 times lower than for the original facility, achieving concentrations of 10 to 100 ng/Nm^3. Even under poor operating conditions, dioxins from the new furnace were an order of magnitude lower (i.e., 200-300 ng/Nm^3). A similar decrease in particulate emissions was observed.

Significant multi-variate correlations were found between a number of trace organic emissions (e.g., dioxins), and operating variables such as combustion air flow rates, underfire/overfire ratio, and refuse feed rates. These variables were identified as potential control parameters which could be used to control incinerator operating conditions to ensure minimal trace organic emissions.

In addition, strong multi-variate correlations were identified between trace organic emissions and easily monitored variables such as carbon monoxide, excess oxygen, nitrogen oxides, and furnace temperature, which could be employed as early warning signals of high trace organic emissions.

RÉSUMÉ

L'incinération des déchets non conditionnés est la deuxième des trois technologies d'incinération à faire l'objet du Programme national d'essais et d'évaluation des incinérateurs d'Environnement Canada. Le principal objectif du Programme est de déterminer quel modèle d'incinérateur et quelles conditions de fonctionnement permettent de réduire le plus les émissions de polluants. L'installation étudiée se trouve à Québec; elle a été construite en 1974. Pour les essais, on a modifié l'un des fours d'incinération pour le moderniser, opération qui a coûté plus de deux millions de dollars.

Le nouveau four a fait l'objet d'une évaluation de 3 mois. D'après les résultats de 19 essais, on a retenu 5 conditions de performance pour les essais plus poussés; on a pu réaliser 13 essais de performance avec succès. On a pesé, échantillonné et analysé tous les déchets et toutes les cendres. Par ailleurs, un réseau informatique étendu a permis de surveiller en "direct" les grandes variables de fonctionnement telles que débit d'alimentation en déchets, températures dans la chambre de rayonnement du four, distribution de l'air, ainsi que les autres paramètres du processus. Les gaz rejetés et toutes les cendres produites ont fait l'objet d'une vaste gamme d'analyses, notamment le dosage des dioxines, furannes, biphényles polychlorés, chlorophénols, chlorobenzènes, hydrocarbures aromatiques polycycliques, gaz acides et de plus de 30 métaux lourds.

Lorsque les conditions de fonctionnement étaient bonnes, les émissions de dioxines venant du four modifié étaient de 40 à 100 fois moins élevées que celles de l'installation originale, les teneurs variant de 10 à 100 ng/Nm^3. Même lorsque les conditions de fonctionnement n'étaient pas favorables, les émissions de dioxines étaient moindres d'un ordre de grandeur (elles se chiffraient à 200 -300 ng/Nm^3). Les émissions de particules avaient diminué dans une mesure comparable.

On a observé des corrélations à variables multiples significatives entre les émissions de certains composés organiques à l'état de traces (p. ex., les dioxines) et divers paramètres de fonctionnement comme le débit d'air de combustion, le rapport admission d'air sous les grilles et au-dessus de la zone de combustion et enfin, le débit d'alimentation. On a pensé se servir de ces paramètres pour régulariser l'incinération afin que les émissions de composés organiques à l'état de traces soient limitées.

Enfin, on a observé des corrélations à variables multiples marquées entre les émissions de composés organiques à l'état de traces et divers paramètres faciles à surveiller comme la teneur en monoxyde de carbone, l'excès d'oxygène, la teneur en oxydes d'azote et la température du four: on pourrait s'en servir pour déceler la formation de quantités importantes de composés organiques à l'état de traces.

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1 INTRODUCTION

Increased difficulties in siting new landfills, along with higher disposal costs, have forced many Canadian municipalities to look at alternative waste disposal methods. One disposal method that has drawn much attention both from the public and decision-makers is incineration in energy-from-waste (EFW) facilities. These facilities offer two important benefits: a significant reduction in the volume of waste for disposal, and possible revenue through energy production. Incineration can reduce the volume of waste to be landfilled by up to 90%, extending the life of present landfill sites and reducing the need for new ones. Furthermore, the energy produced by the burning of municipal solid waste provides revenue for the owner and reduces the need for imported fuels.

The concerns that have been raised repeatedly regarding both existing and proposed EFW facilities are the environmental and health effects of emissions. As a consequence of these concerns, and those raised by the Expert Advisory Committee on Dioxins (Ministers of Health and Welfare Canada and Environment Canada), which recognized refuse incineration as a significant controllable input of dioxin into the atmosphere (1), an action plan was developed.

The Action Plan addressed two key committee recommendations: the expansion of efforts to define the optimal design and operating conditions for municipal and industrial incinerators to minimize the production and emissions of dioxins; and the characterization of the best available incineration technologies in Canada through an environmental monitoring program. In response to these two important recommendations, the National Incinerator Testing and Evaluation Program (NITEP) was established by Environment Canada. Through an extensive five-year program, NITEP is investigating three of the most popular incinerator designs, assessing the new add-on pollution control technologies and exploring new incinerator systems. Attempts are being made to correlate combustion conditions with emissions of trace organics (dioxins, furans, etc.) and inorganics (metals and acid gases). Numerous studies have been made to define the best "operating window", to ensure that optimal combustion conditions are maintained to minimize or eliminate emissions of concern.

In the first phase of NITEP, criteria for the selection of EFW facilities suitable for testing and evaluating were established. Based on the established criteria, three candidate generic incinerator designs were selected. These designs exemplified projected future trends in incinerator technologies in Canada. The three incinerator designs chosen were:

- a two-stage combustion (modular technology) system,
- a mass burning system employing moving grates, and
- a refuse derived fuel system using semi-suspension burning.

The first candidate studied was the two-stage combustion facility in Parkdale, Prince Edward Island. This work was successfully completed in early 1985 and a summary report was released in September 1985 (2).

The second candidate selected was the mass burning system in Quebec City, owned by the Communauté Urbaine de Québec (CUQ) and operated by Monterey Inc., and is the subject of this report.

The third facility is the refuse derived fuel Mid Connecticut Resource Recovery Project, in Hartford, Connecticut. This facility was designed and constructed by Combustion Engineering Inc., and the owner is the Mid Connecticut Resource Recovery Authority. Testing of this facility will begin in the summer of 1988.

The combustion assessment program for the Quebec incinerator consisted of an extensive field effort to collect process and emission data over a range of different operating conditions. In this respect, it was very similar to the effort undertaken at the Parkdale, P.E.I., facility. However, since the Quebec facility was designed more than a decade ago, it was not considered comparable to modern mass burning systems and a design modernization study was added to the original program. The modernization study identified the modifications required to upgrade the facility to a modern state-of-the-art design.

A considerable amount of data was generated during the Quebec City mass burning incinerator testing program. The data and conclusions were compiled into six separate volumes.

Volume I - Summary Report, outlines all significant results and conclusions of the program.

Volume II - Main Report, contains a complete description of the program and detailed discussion of the results. It also presents the field and laboratory data in a reduced form for both the characterization and performance test phases.

Volume III - Methodologies, contains a complete description of all methodologies employed. This volume also addresses all modifications made to standard reference procedures and the rationale.

Volume IV - Detailed Data Report, summarizes all of the data by operation mode and test run and provides the complete analytical results.

Volume V - Quality Analysis/Quality Control Report (by an independent group), provides an independent unbiased assessment of the program's sampling and analytical methodologies.

Volume VI - Leachate Assessment Report, presents the results of the leachability of both organic and inorganic contaminants on a short- and long-term basis.

Although Volumes II to VI have not been published, limited copies on microfiche are available from the Industrial Programs Branch.

2 PLANT DESCRIPTION

2.1 General

The Quebec municipal solid waste (MSW) incinerator plant is owned by the Quebec Urban Community (QUC) and located in the northeast end of Quebec City. The plant receives municipal, commercial, and suitable industrial solid waste collected by the QUC, several other municipalities, and private contractors. It is rated for 900 tonnes per day of refuse and utilizes moving grate, waterwall incineration technology to burn refuse as-received. Super-heated steam is produced using flue gas heat recovery boilers. The resulting ash is transported to a designated landfill site by private contractor.

Montenay Inc. operates the plant under a comprehensive operations contract that includes the responsibility for all maintenance and servicing. All steam generated is sold exclusively to Reed Paper Ltée, and is supplied at a relatively steady flow and specified pressure range. The incinerator operates 24 hours per day, 363 days per year with two complete (24-hour) shutdowns for major inspection and maintenance of the steam plant and steam supply line to Reed. Although the plant consists of four independent furnaces, normally only three of the four units are in operation at any one time.

The plant was originally designed and built in 1974 under the direction of Surveyer Nenningera Chênevert Inc., with Dominion Bridge-Selzer Inc. providing the major equipment. The incinerator furnaces were designed by Von Roll Inc. and built by Dominion Bridge-Selzer Inc. In 1979, a lined waterwall arch was installed above the drying and burning grates of each incinerator. These modifications were designed for the QUC by Shawinigan-Lavalin Inc. assisted by Dominion Bridge-Selzer Inc. In 1985/86 the consortium of Lavalin Inc. modernized unit 4 prior to the NITEP field test.

2.2 Plant Components and Design

The principal plant elements as shown in Figure 2.1 are as follows:

i) a weigh scale system for incoming trucks (not shown in Figure 2.1);
ii) a fully enclosed, single-side entry, refuse tipping, storage pit and crane system;
iii) four mass-burning incinerators burning as-received refuse, each nominally rated at 227 tonnes per day;
iv) an ash quench tank, drag chain, ash storage pit and crane system; and
v) a single flue stack (approximately 55 m in height) common to all four incinerators.

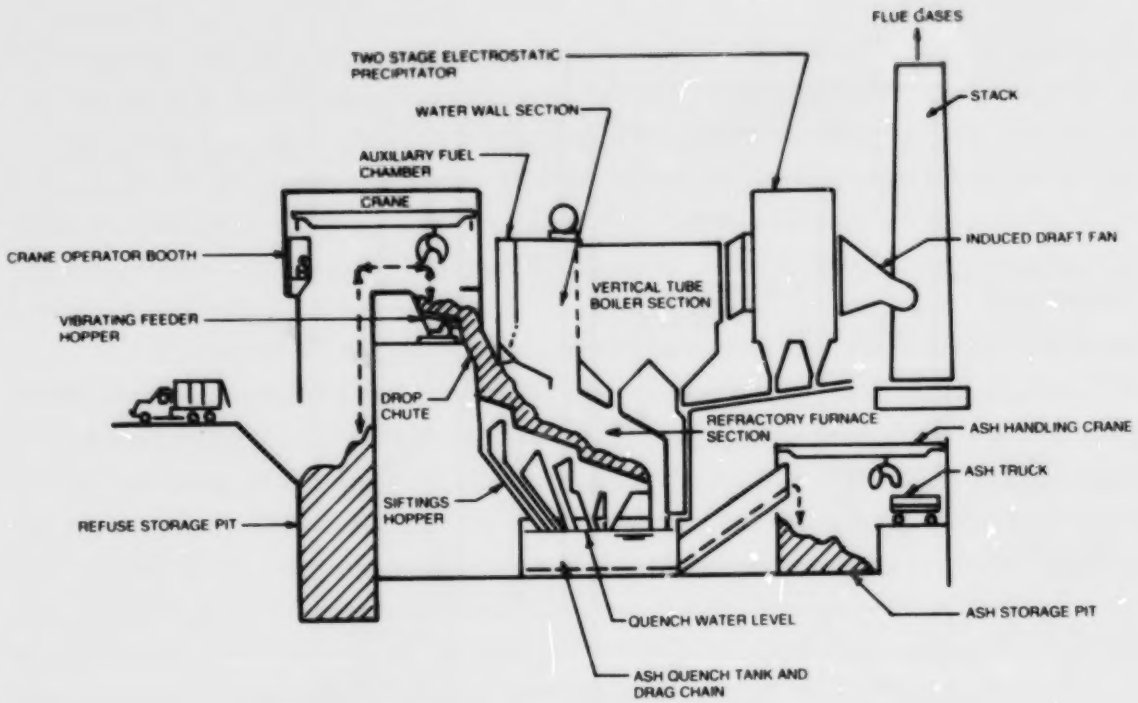


FIGURE 2.1 QUEBEC INCINERATOR SCHEMATIC CROSS-SECTION

As further illustrated in Figure 2.2, each incinerator consists of:

a) a vibrating feeder-hopper,
b) a water-cooled feed chute,
c) drying/burning/finishing reciprocating grates,
d) a refractory-lined lower furnace burning zone,
e) a waterwalled partially-lined furnace radiation chamber,
f) a vertical tube, mechanically-rapped waste heat recovery boiler with superheater and economizer tube sections,

In addition, each incinerator is equipped with:

a) a two-stage electrostatic precipitator,
b) an induced draft fan, and
c) an ash quench tank with a drag chain ash removal system.

2.3 General Operation

Trucks carrying refuse pass over a truck scale at the entry to the site and dump their loads into the refuse storage pit. Any materials deemed inappropriate for

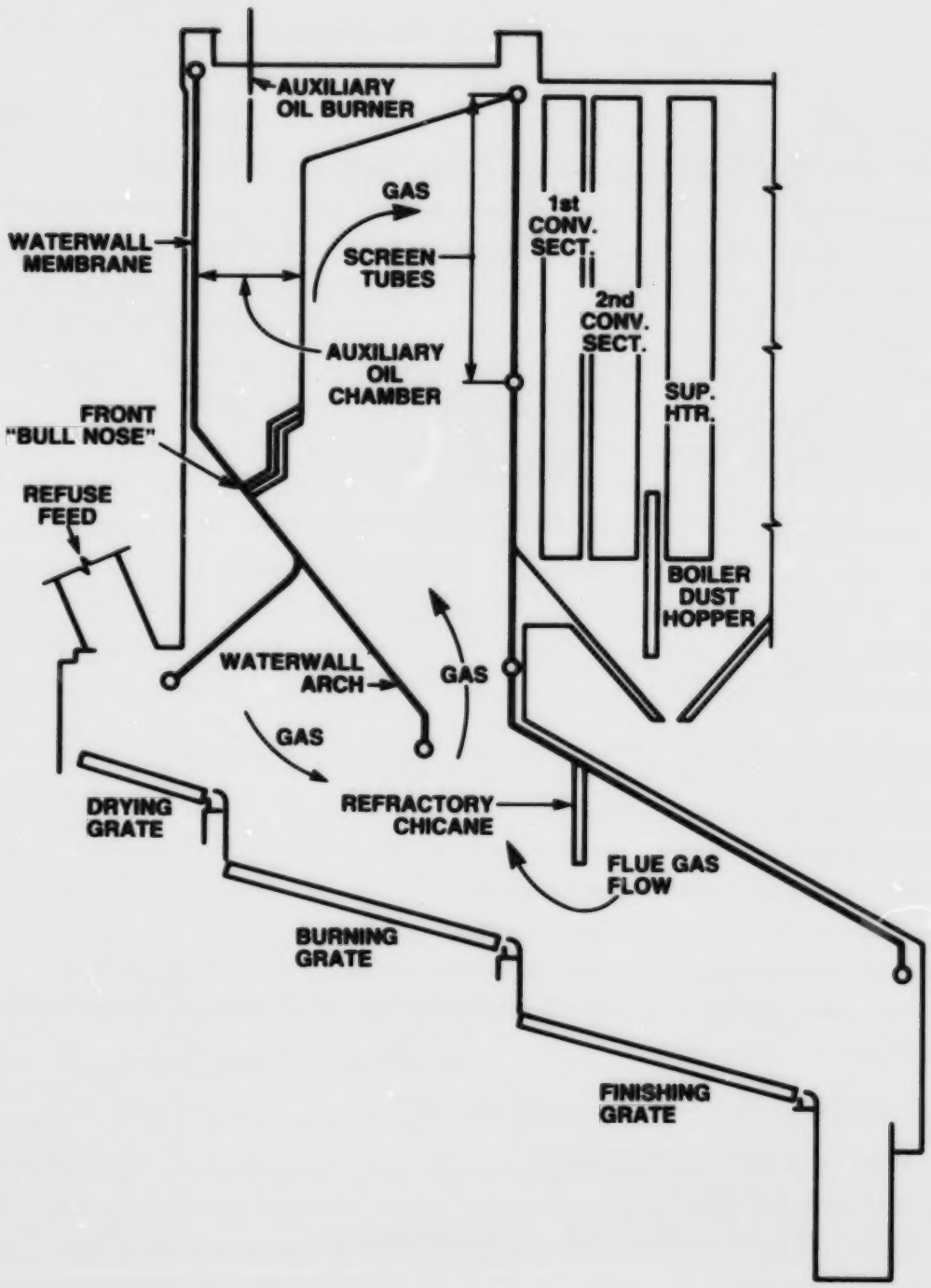


FIGURE 2.2 QUEBEC INCINERATOR DESIGN (1978)

incineration, such as large appliances, are removed from the pit by a crane and transferred to a landfill site or scrap metal facility. Two overhead cranes are used to charge refuse into each vibrating feeder/hopper system as well as to clear the tipping face of the pit or to pre-mix waste. Refuse is fed by the vibrating feeder on an as-required basis onto the incinerator drying grate via the water-cooled feed chute. The vibratory feeder automatically maintains a column of refuse or "plug" in the feed chute to prevent undesirable air from entering the combustion area.

Three sets of moving grates form the furnace floor. The burning wastes are moved down the length of the furnace by the reciprocating motion of the grates. The first grate (drying grate) meters the flow of refuse from the feed chute onto the main combustion grate (the burning grate) and in turn the burning grate discharges partially burned waste onto the third grate (finishing grate) for final "burn-out". Ash is discharged off the end of the third grate into the quench tank below. Each grate can be operated independently by speed-adjustable hydraulic rams. Under normal operating conditions, the speed of each of the three grates is adjusted to obtain the desired throughput and the best 'waste-burned profile' on each grate. The grates are placed on a 15° slope with vertical drops between the grate sets.

Fine materials or "siftings" which drop between the grate blocks are collected in hoppers below the grates and discharged into the quench tank. The siftings hoppers also act as a plenum, providing a means of admitting primary (underfire) combustion air through the grates and into the furnace. Each hopper is pressurized by the primary combustion air fan. Air leaves the hoppers and passes up between the grate block rows, thereby supplying a relatively even distribution of air to the refuse bed and the combustion zone above. This air also cools the grates.

The lower furnace wall (burning zone) is lined with an alumina refractory. The roof of the furnace and the radiation chamber are constructed with side-by-side welded tubes through which boiler water is circulated to provide cooling and heat recovery. This construction is referred to as the waterwall. The lower portion of the waterwall is coated with a heat-resistant refractory lining to protect the tubes from direct exposure to the flames. The roof and the upper sections of the waterwall in the radiation chamber near the boiler inlet are exposed to the flue gas to improve heat recovery.

Flue gases leaving the radiation chamber or vertical flue section of the combustion chamber enter the heat recovery boiler via vertical screen tubes. The boiler is a vertical multi-tube boiler with convection, superheater and economizer sections

which are cleaned by a mechanical rapping system. Gas temperature at the boiler outlet drops to between 200°C and 280°C, depending on the operating condition of the boiler.

Cooled flue gases leaving the boiler section enter a two-stage electrostatic precipitator for particulate removal, and finally exit to the atmosphere via an induced draft fan and the exhaust stack.

2.4 Design Modernization

In January 1985, Lavalin Inc. was retained by Environment Canada to investigate the implications and costs of upgrading the Quebec MSW incinerator to a state-of-the-art design. Based on that study, the Quebec Urban Community decided to proceed with reconstruction of one of the four furnaces.

2.4.1 Furnace Flow Modelling. To assist the design engineers in optimizing furnace configuration and combustion air flow, a furnace flow modelling study was conducted by NELS Inc. for MacLaren Plansearch Inc. (a division of Lavalin).

The main objectives of the furnace modelling study were as follows:

a) to improve the turbulence at the secondary (overfire) air zone to provide thorough mixing of combustion air and combustible gases;
b) to examine the effect of increased retention time in the furnace achievable by removing the existing auxiliary burner chamber and thus increasing the effective furnace chamber volume;
c) to examine the effects of various furnace chamber configurations and secondary (overfire) air rates on flow distribution into the boiler inlet;
d) to optimize the location and size of the secondary air nozzles and improve the nozzle design to achieve thorough mixing;
e) to optimize the shape and location of new "bull-noses" (see Figure 2.3) to achieve b) and c); and
f) to investigate the impact of different front-to-rear secondary air ratios on a), b) and c).

A 1/6-scale airflow model of one of the incinerators, was fabricated of Plexiglas and wood. The model design was flexible enough to enable the insertion or deletion of different wall or roof panels to allow testing of various furnace design configurations. In total, 51 recorded model test runs were conducted on both the 1978 design (Figure 2.2) and various proposed configurations.

Based on an assessment of the flow patterns observed, the following conclusions were made:

- The 1978 configuration effectively used only a fraction of the available upper furnace radiation chamber.
- The 1978 configuration resulted in a high particulate carry-over rate from the burning and finishing grates to the lower level of the boiler inlet. This high carry-over was caused by higher upward velocities which occurred with the narrow arch opening.
- The high gas velocity at the boiler inlet was probably one of the factors causing excessive erosion on the lower part of the boiler inlet screen tubes.
- The retention time in the radiation chamber was limited by high gas velocity and the presence of a burner chamber.
- Direct flame impingement on the boiler screen tubes probably occurred.

To correct these problems, the modified furnace configuration shown in Figure 2.3 was selected. A lower bull-nose was proposed to provide a furnace configuration similar to recent Von Roll designs which maximize radiation reflection onto the burning and finishing grates to improve ash quality. Another purpose was to "pinch off" the combustion gases in the furnace leaving the finishing grate zone to ensure complete burnout of the volatile gas. Several variations of the lower bull-nose configuration were tested to determine an optimum shape.

An upper bull-nose in the furnace was proposed to:

- reduce gas vortices in the upper chamber;
- improve gas distribution in the upper radiation chamber; and
- reduce stratification of the combustion gas at the boiler inlet.

In summary, flow modelling confirmed that the proposed modifications should produce good mixing and create a high turbulence zone above the overfire air nozzles, improve retention time, and improve the flue gas distribution at the boiler inlet.

2.4.2 Final Modifications. Based on the above furnace modelling results, the following construction modifications were completed in March 1986 on unit 4:

a) **Radiation chamber modification.** The bull-nose design was implemented and the waterwall arch was removed to prevent high flue gases velocities, to provide good mixing of overfire (secondary) air in the lower portion of the chamber, and to improve gas distribution into the boiler. Other radiation chamber modifications

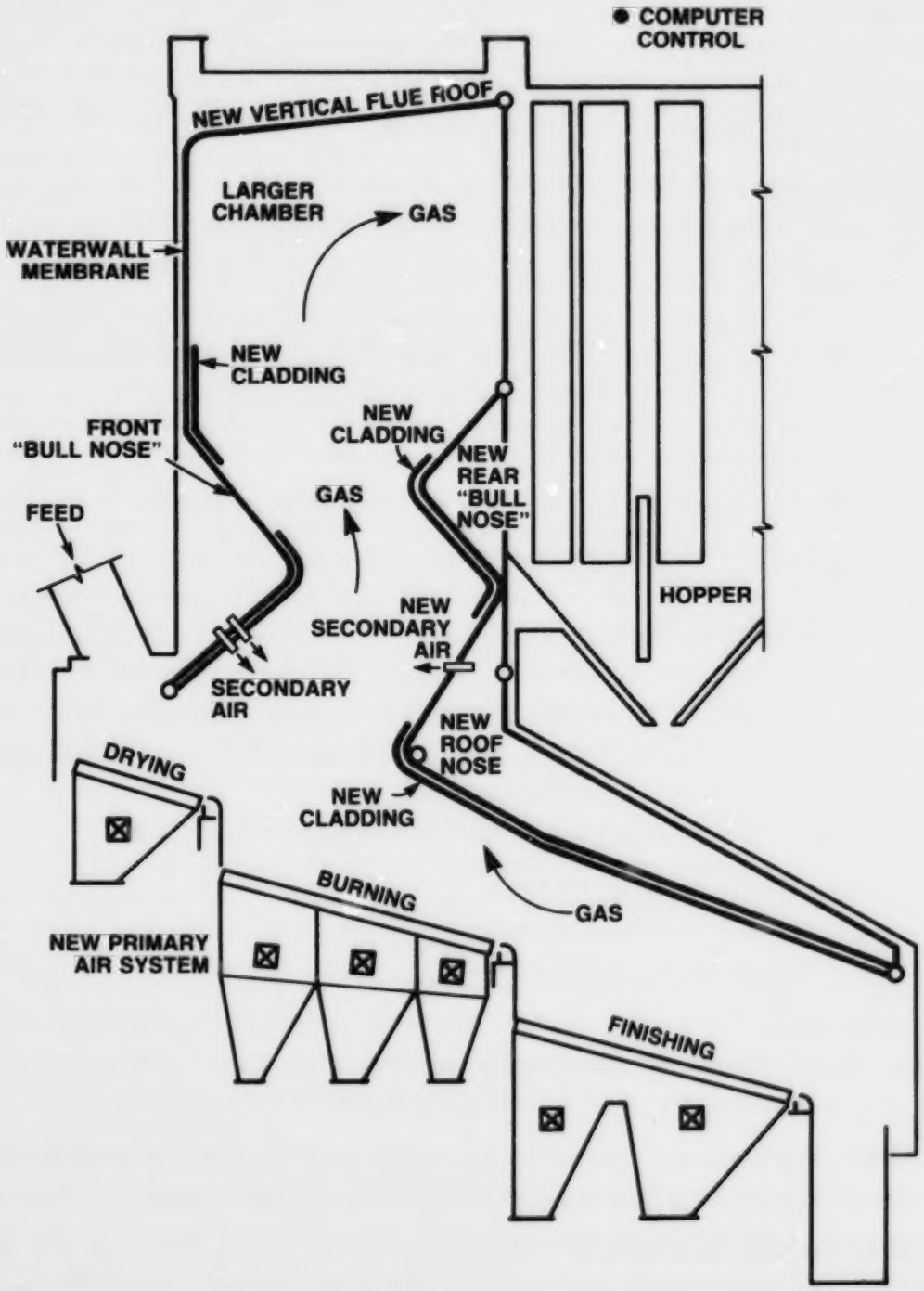


FIGURE 2.3 MODIFIED QUEBEC INCINERATOR DESIGN (1986)

included the removal of the auxiliary oil burner cage to increase the radiation chamber volume by approximately 32%, thereby increasing flue gas residence time.

b) **Primary air distribution modification.** To improve primary air distribution and control, additional siftings hoppers and air zones were installed beneath the grates, along with control dampers and flow monitors to permit automatic control of the underfire air split to the grates. As shown in Figure 2.4, the modified primary air system provides nine separate zones for underfire air. The individual flow controllers distribute a preset percentage of the total flow to each hopper, and the total primary air flow and distribution splits are adjusted continuously.

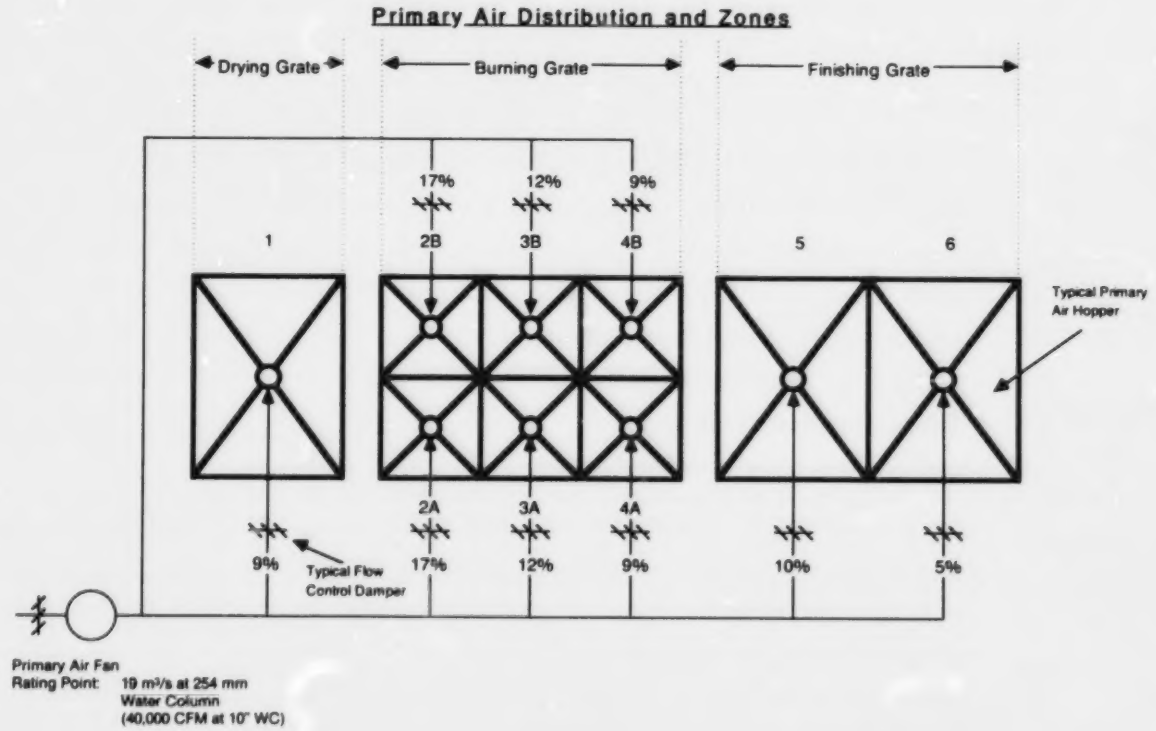


FIGURE 2.4 QUEBEC INCINERATOR COMBUSTION MODIFICATIONS

c) **Overfire air supply system modifications.** The overfire (secondary) air system modification shown in Figure 2.3 was made to supply overfire air to the flue gas from both the front and rear bull-noses through multiple new high-velocity jets. To achieve the necessary control between the front and rear air nozzles, powered

isolating dampers and flow controllers (primarily controlled relative to the combustion gas boiler inlet temperature) were installed in the respective ducts. With the modified design, secondary air is introduced into the furnace through 10 nozzles located in the front wall bull-nose and 9 nozzles in the rear wall nose. Ambient air is supplied by a secondary air supply fan at a pressure of 500 mm water gauge. The secondary air system was also designed to provide a ratio of 3:1 front/rear or rear/front air with a ratio of 65/35 primary/secondary air. The system has the capacity to provide a wide range of ratios to suit varying operating conditions.

d) **Instrumentation and control modifications.** In order to bring the test unit up to "state-of-the-art" in automatic controls, the following major modifications were made:

- A Bailey Network-90 computer system was installed to provide process information to the operators and to automatically regulate the following operating parameters:
  - steam flow rate,
  - grate speed,
  - primary air flow and distribution,
  - boiler inlet temperature,
  - flue gas oxygen level, and
  - secondary airflow and distribution.
- The grate hydraulic control system was modified to automatically vary the grate stroke frequency in response to boiler steam flow.
- An excess air (oxygen monitor) feedback control system tied to the grate speed controller was installed.
- The primary airflow controller was modified to automatically respond to steam set-point and/or the excess air level (oxygen monitor).
- Automatic flow control for the primary air distribution system was installed to maintain the desired air proportioning ratios to each hopper zone, including under the drying and finishing grates.
- A secondary air supply control system to automatically vary the flow rate and the ratio of front/rear air in response to temperature readings in the upper part of the radiation chamber was added.

3 PROGRAM DESCRIPTION

3.1 Approach

The Quebec incinerator test program was designed to address two major NITEP objectives:

1) to evaluate the process performance of a state-of-the-art mass burning incinerator (refuse handling, combustion and heat recovery), and
2) to characterize emissions under different operating conditions (relating the implications of incinerator/furnace operating conditions to the emissions of particulates, metals and trace organic compounds).

The sampling methods and protocols developed during the NITEP P.E.I. Program (2) were reviewed, and adopted or modified where applicable. Sampling and analytical protocols are presented in Chapter 4.

As part of a Quebec provincial monitoring and assessment program, an extensive amount of stack testing had already been undertaken at the Quebec facility (acceptance testing, annual particulate testing, particle size characterization, and emissions testing for hydrogen chloride, metals, dioxins, and furans). This provided the necessary background data with which to assess any combustion and emission improvements resulting from the design modifications.

3.2 Site Preparation

Preparation of the site for testing involved selection of the unit for testing, selection of sampling locations, and modification and installation of the sampling equipment, as well as the data acquisition system. Unit 4 was selected for modernization and testing because of the following advantages:

i) a reasonable exhaust gas sampling location;
ii) a large area available to install the continuous gas monitoring equipment;
iii) ready access to the open sections of property behind the main building, and
iv) the least interference with the normal operation of the other units.

The sampling locations (shown on Figure 3.1) and the rationale for their selection were as follows:

i) **Refuse** - Representative samples of incoming refuse were collected (Location no. 4) during each test run to determine refuse composition and heat content. The time

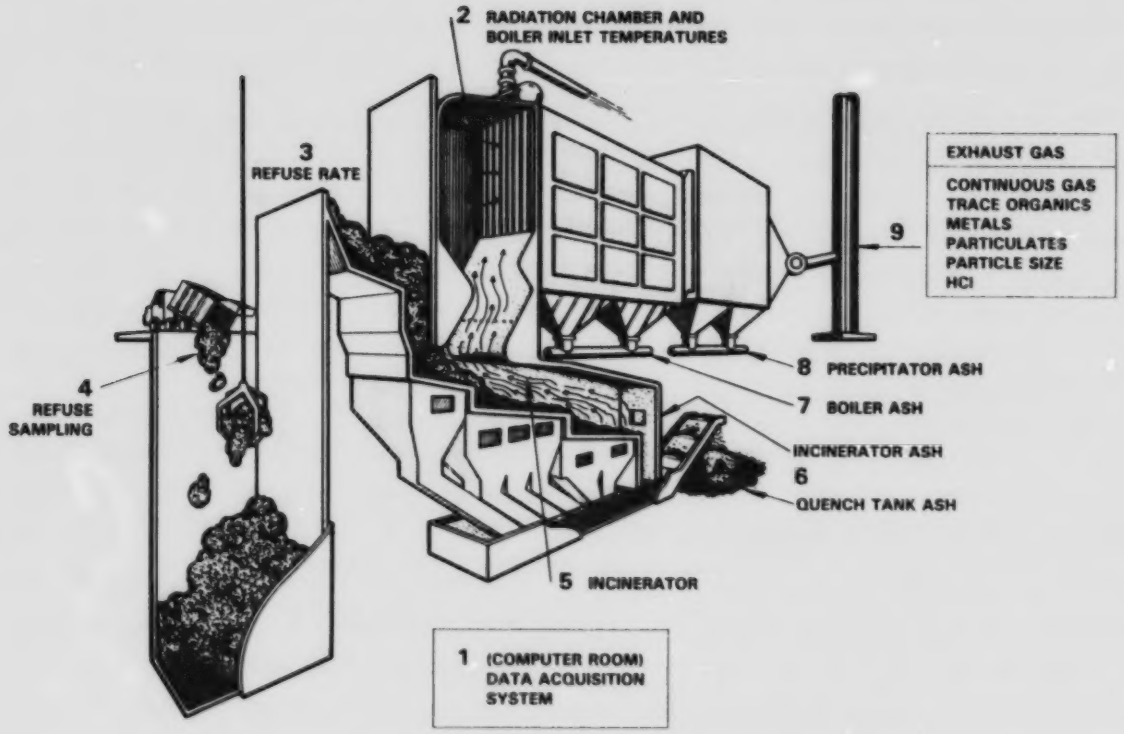


FIGURE 3.1 QUEBEC INCINERATOR SAMPLING LOCATIONS

and weight of each charge of refuse was recorded (Location No. 3) to obtain mass balances.

ii) **Radiation Chamber Temperature** - Because low temperature zones in the furnace are considered to be one mechanism in the formation of dioxins and furans and the failure to destruct trace organic compounds, a horizontal thermocouple grid was installed in the radiation chamber just above the overfire air nozzles and a vertical grid was installed at the boiler inlet (Location no. 2) to determine whether any low temperature zones existed.

iii) **Incinerator Ash** - Ash quality is often used by operators as a primary indicator of satisfactory operation of the incineration process. To assess ash quality, ash samples were taken directly from the finishing grate through an opening (installed for the NITEP tests) in the rear access door of the radiation chamber (Location no. 6).

iv) **Quench Tank Ash** - To determine the weight reduction in waste achieved by incineration, it was necessary to measure the total quantity of bottom ash generated. Boiler/economizer ash and precipitator ash were diverted from mixing with the quench tank ash to allow separate ash streams to be collected. All the wet bottom ash accumulated in the ash pit (quench tank ash) during each test period was weighed using the plant's main truck scales (Location no. 6). Grab samples of ash were taken directly from the truck to determine water content and combustibles.

v) **Boiler/Economizer Ash** - Modifications were made to the ash chute from the heat recovery boiler to collect, quantify and sample all ash from the boiler/economizer hoppers (Location no. 7).

vi) **Electrostatic Precipitator Ash** - All precipitator ash was collected and sampled (Location no. 8). Precipitator ash quantity and colour provide a first order indication of collection efficiency and particulate emission.

vii) **Combustion Gas** - Continuous gas samples were extracted from a high turbulence zone in the vertical duct section at the exhaust of the forced draft (FD) fan. Organics, particulate, particle sizing, heavy metals, mercury, and acid gas samples were taken from the horizontal section of the unit 4 exhaust duct. The gas sampling platform was designated (Location no. 9).

viii) **Data Acquisition** - All process, continuous gas data and temperatures were monitored throughout the tests via a data acquisition system. Relevant process data were gathered, recorded and displayed on a real-time basis (Location no. 1).

3.3 Characterization Testing

The purpose of the characterization testing was to familiarize the test crew with the test incinerator, to implement and refine the data handling and sampling systems, and to assess the operating capabilities of the incinerator to define acceptable process test conditions for an optimum performance test matrix. Characterization tests essentially involved changing only one process parameter and operating at steady conditions to identify how the unit would respond and how each parameter affected the overall performance of the unit. To complete as many trials as possible, the sampling time for the characterization tests was limited to a maximum of two hours.

All process data and continuous gas analyzer data were continuously monitored prior to, during, and after each characterization test period, as illustrated in Figure 3.2.

These results were used to assist field personnel in establishing the effects on emissions caused by operational changes, and also to ensure that short-term fluctuations did not misrepresent the character of the particular operating mode at the time.

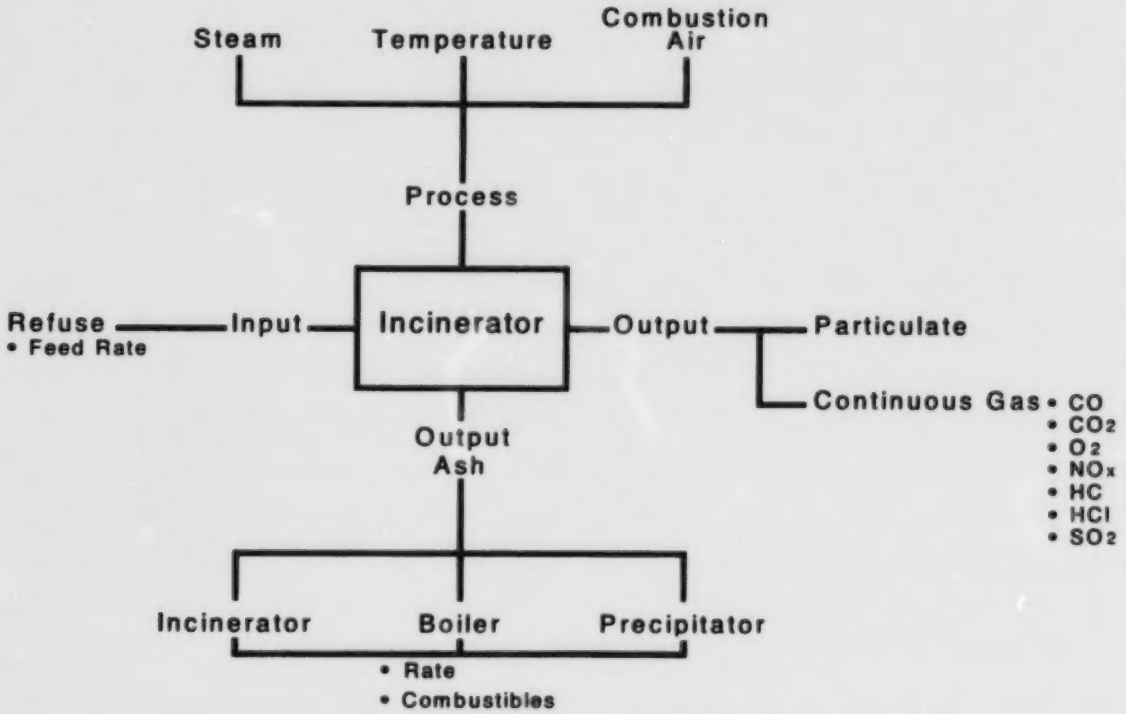


FIGURE 3.2 CHARACTERIZATION TEST SAMPLING PARAMETERS

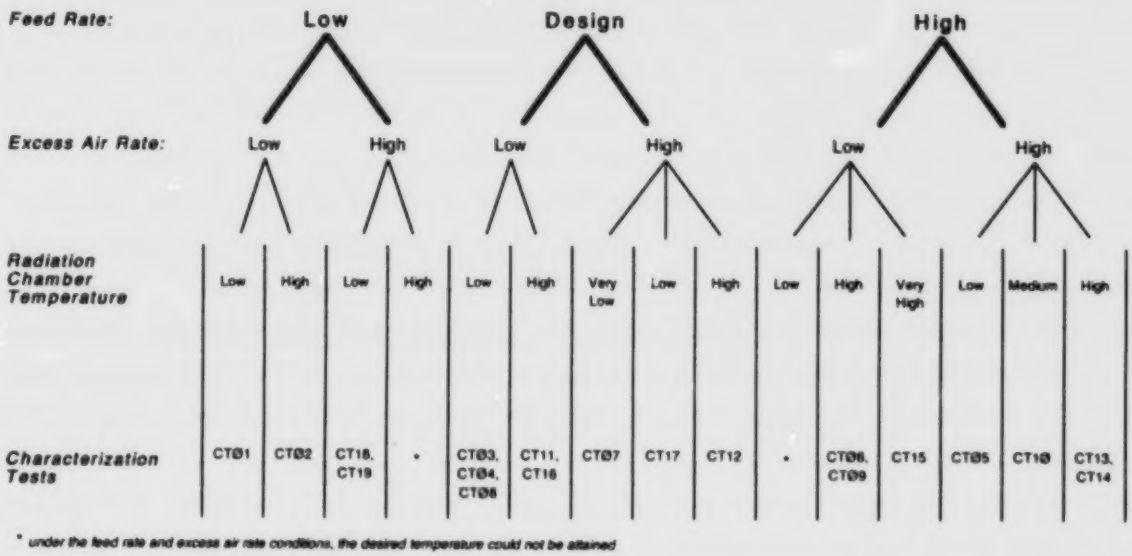
Since only a limited number of tests were possible, a hierarchy of process parameters was established to ensure that information for the most critical parameters affecting the overall operation would be obtained, leaving the less critical parameters for last. The process parameters considered during the characterization tests and the order in which these parameters were optimized was as follows:

1) refuse feed rate and/or steam rate,
2) excess air,
3) primary/secondary air split,
4) primary air distribution,
5) burning grate refuse bed depth,
6) finishing grate ash bed depth,

7) front/rear secondary air ratio, and

8) radiation chamber temperatures.

Figure 3.3 shows the different operating conditions investigated during the characterization tests, based on the above process parameters. Three waste feed rates were chosen: low, design and high. For each feed rate, both low and high excess air rate conditions were selected. An attempt was also made at each excess air condition to operate at low and high radiation chamber temperatures. However, some temperature conditions were not considered feasible due to the poor quality of the refuse at the time and/or simply the fact that the attempted condition was impractical. In all, 19 characterization tests were completed to demonstrate how incinerator performance and emissions changed under different operating conditions.



* under the feed rate and excess air rate conditions, the desired temperature could not be attained

FIGURE 3.3 CHARACTERIZATION TEST OPERATING CONDITIONS

From the characterization test (CT) phase, the following general assessment of the incineration system performance was developed, which provided the rationale for selecting the performance test (PT) conditions.

- The incineration system was capable of stable operation at all three rates tested (20, 28 and 32 t/h steam). Carbon monoxide levels below 100 ppm under high steam rates and below 50 ppm at low and design feed rates could be readily achieved.

- The primary/secondary air ratio of approximately 60:40 appeared to provide the most stable operation with relatively low carbon monoxide concentrations. On the other hand, operation of the incinerator with a ratio of 90:10 resulted in the highest carbon monoxide concentrations. This strong interrelationship between primary/secondary air ratio and carbon monoxide levels was identified as an important consideration to be addressed in the performance tests.
- Control of the primary/secondary air ratio as either a fixed ratio or a variable ratio in response to the changing radiation chamber temperature showed no significant advantage one way or the other. However, with fixed ratio control, the radiation chamber temperature tended to vary more. Since combustion experts and regulatory agencies emphasize temperature as one of the primary requirements for the destruction of trace organics, the temperature-controlled primary/secondary air ratio was chosen as the preferred operating mode for the performance test phase.
- When the proportion of primary air supplied to the first burning zone exceeded Von Roll's recommendations, a shallower burning bed depth occurred on the finishing grate zone with an apparent improvement in ash quality. However, this resulted in an increase in particulate lift-off and glowing particle carry-over into the boiler. To minimize the emission rates and provide performance results that were consistent with modern practices, the primary air distribution recommended by Von Roll was adopted as the preferred operating mode for the performance tests.
- The changes made to the secondary air distribution (i.e., front to back air supply ratio) did not appear to significantly affect performance. Therefore, the temperature-controlled operating mode, rather than the fixed ratio mode, was selected for the performance tests.
- Total primary air appeared to be a critical parameter in achieving low carbon monoxide levels and low particulate emission rates (i.e., very high primary air rates resulted in high carbon monoxide levels and a high particulate lift-off rate). As a result, the total primary air rate was identified as a key parameter to investigate during the performance test phase.
- In general, good operating conditions were achieved by maintaining an even burning bed on the grates and avoiding flame impingement on the boiler inlet tubes. This usually coincided with good primary/secondary air ratios (60:40) and low carbon monoxide concentration operating conditions. Since carbon monoxide peaks coincided with shifts from steady operation to upset conditions, and since the carbon monoxide analyzer was a reliable instrument during the test program, carbon

monoxide levels were established as a key monitoring parameter for the performance tests.

- Automatic control of the grate speeds in response to steam rate and oxygen levels provided steady repeatable performance. Since, under manual control, a number of operating modes was difficult to maintain, automatic control of the grate speeds was selected for the performance test runs.
- During the characterization test runs, a wide range of excess air levels (40 to 162%) and radiation chamber temperatures (805 to 1099°C) occurred. While other parameters seemed to have equally significant effects on the system's performance (particularly on carbon monoxide levels), these two parameters were considered to be significant from the perspective of controlling the incinerator. Since many combustion experts and regulatory agencies emphasize operating temperatures to ensure trace organic destruction, temperature was selected as one of the primary parameters in the performance test conditions.

3.4 Performance Testing

Based on a thorough assessment of the characterization tests, five operating conditions were selected for the performance test matrix, as shown in Figure 3.4. These operating modes were selected to obtain test results at three steam rates (low, design and high) as well as good and poor operating conditions at the design steam rate. As illustrated in Figure 3.4, three out of the five operating conditions tested were at the design steam rate, one operating condition was at the low steam rate, and one operating condition was at the high steam rate.

Only one operating condition was selected from each of the low and high steam rate conditions because these are not typical. Three operating modes were selected at the design steam rate to obtain sufficient data for as many different operating conditions at normal load as budget constraints permitted. The adopted approach permitted comparison of "good" operating conditions at the design steam rate with good operating conditions at the other two steam rates. As well, comparison of good operating conditions with poor operating conditions at the design steam rate was possible.

The different performance test operating modes were established primarily by changing the steam rate set-point and the primary (underfire) air and secondary (overfire) air rates. Each operating mode resulted in different combustion temperatures, levels of oxygen, and carbon monoxide emissions.

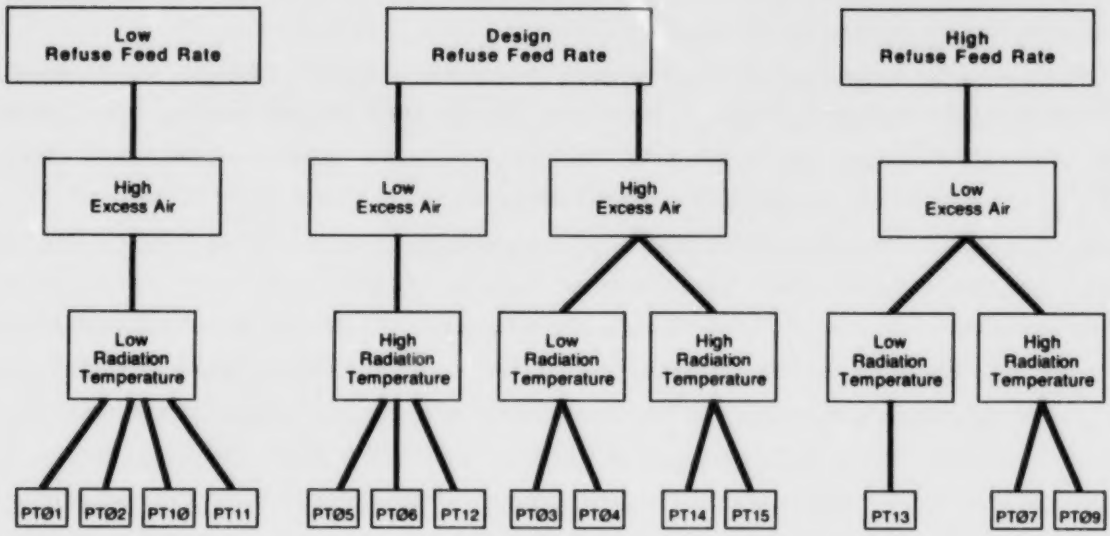


FIGURE 3.4 PERFORMANCE TEST OPERATING MODES

Each performance test run involved a minimum of 10 hours of operation, over and above the time required to bring the unit to steady-state before each performance run was started. A 10-hour test duration provided a minimum of four hours of manual train sampling, such as for dioxins.

Triplicate testing, as opposed to duplicate testing, is generally the preferred approach for performance testing. Duplicate testing would allow a greater number of operating conditions to be tested, but triplicate testing increased the statistical reliability of the data obtained. The completed Performance Test program consisted of three operating conditions being triplicated and two being duplicated. The first test run (PT-1) was carried out as a preliminary shakedown run at the low steam rate. This run enabled the sampling teams and plant operators to become familiar with, and responsive to, the requirements of this extensive incinerator performance evaluation program. Another test (PT-8) had to be aborted when one of the trace organic isokinetic sampling trains experienced equipment failure. Thirteen of the fifteen scheduled performance test runs were completely successful.

PT-13 is set apart from PT-07 and -09 since PT-13 was deemed inconsistent with the target parameters. During PT-13, test operators experienced considerable difficulty in maintaining steady operation because of wet slugs of refuse and slag build-up restrictions in the combustion chamber. Since conditions experienced during this test run

were not comparable with the other two tests (PT-07 and -09) of this group, PT-13 was not considered to represent "good operating conditions at high burning rate".

The triplicate test runs (i.e., good operating mode conditions at the three burning rates) were scheduled so that the time between the first and third tests of each series was extended as long as the program timing permitted. This allowed time for the waste in the pit to be replaced with new and possibly different quality waste before the final triplicate test was undertaken. For example, the third low, design and high burn rate test runs were completed nine, nine and seven days after the first test run of each burn rate group, respectively.

The performance test parameters sampled and monitored are shown in Figure 3.5.

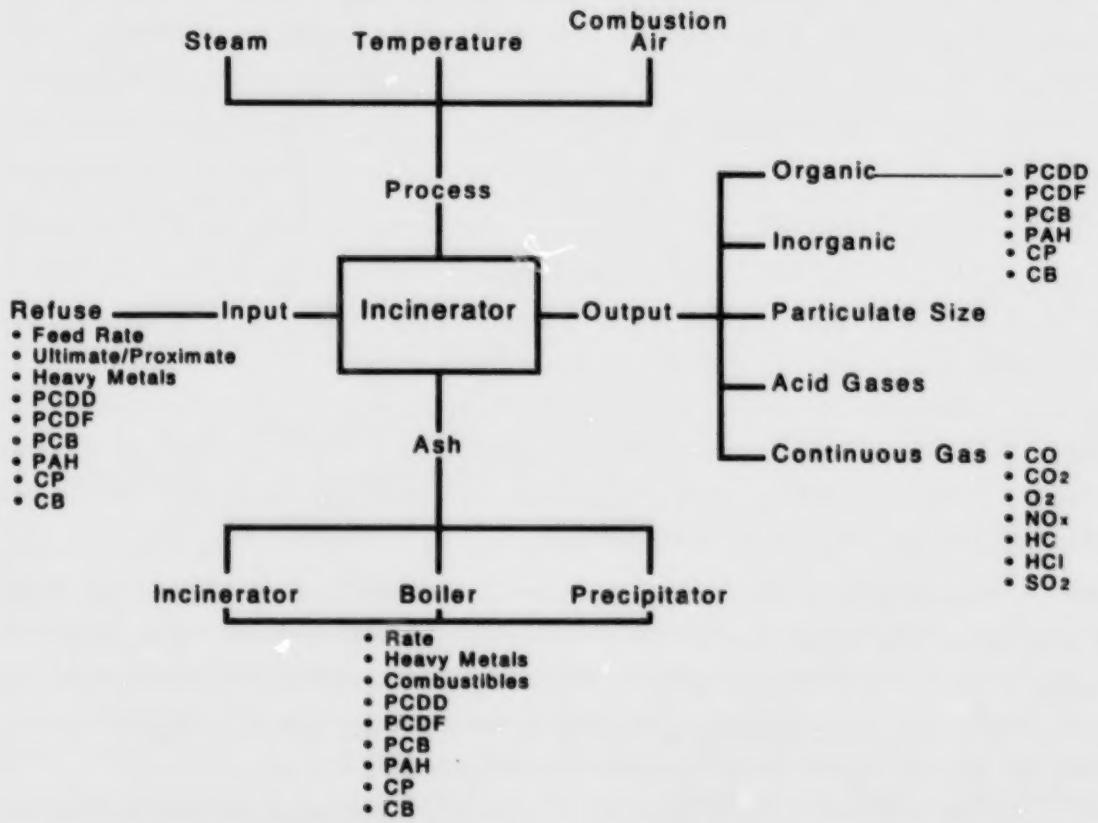


FIGURE 3.5 PERFORMANCE TEST SAMPLING PARAMETERS

4 SAMPLING AND ANALYTICAL PROTOCOLS

4.1 Overview

All instrumentation and sampling methods employed during the test program used recognized standards where available. Any deviation from these recognized standards was documented, including the rationale for the change. Previously used methodologies, developed for the NITEP P.E.I. (2) and Air Pollution Control Technology (3) studies, were adopted where possible. The methods and protocols selected were reviewed in terms of their application to the Quebec mass incinerator and adapted where necessary to the different site conditions.

Samples of refuse and ash discharged by the incinerator, boiler/economizer and precipitator were collected and analyzed for metals and trace organics. Samples of stack gases (manual and continuous) were taken in the flue gas exhaust. Where applicable, sample recovery was performed using recognized standard methods or by the "best practical procedure" if some variation from standard protocols was necessary. This section of the report provides a brief outline of the sampling methods used and the organic and inorganic analytical protocols employed.

4.2 Refuse

4.2.1 Sampling. During each performance test, refuse sampling was carried out by randomly selecting at approximately one hour intervals an incoming truck to discharge a portion of its load of municipal refuse onto a steam cleaned floor. The garbage collected from four to five trucks per test was spread out and sorted to remove large pieces of metal and undesirable materials. The refuse was then placed into a shredder using a mini-loader. The shredded material was coned and quartered and a representative sample was obtained for analyses. Further sample processing such as drying, shredding or milling was carried out at a laboratory prior to analyses.

4.2.2 Charging Rate. The total weight of refuse charged to the incinerator during the test period was determined on an hourly rate basis. Each crane bucket load was weighed immediately before charging the load into the feed hopper. The time, weight and charge description were recorded. The weight was also logged by the data acquisition system for the calculation of the real-time efficiency display.

The scales used for weighing had a range of scale error within 0.25 percent for the range of loads weighed. Scales were zeroed using the crane bucket before and after

each test day. The crane bucket weight was also measured prior to and after each test, to verify that the scale was still calibrated.

4.3 Ash Sampling

Incinerator ash samples were taken from a specially designed port located directly across from the finishing grate. A stainless steel shovel was inserted into the furnace every 15 minutes at different locations to obtain a representative sample. The ash was transferred to a stainless steel container with dry ice, cooled, then transferred to a tared 200-L (45-gallon) drum. At the completion of the test, the drum contents were combined, coned and quartered on a precleaned floor. One of the coned quarters was placed into a single 23-L (5-gallon) plastic-lined pail.

Boiler/economizer ash was obtained by diverting the ash into a tared 200-L drum 30 minutes after the start of each run. At the completion of the test, the ash was thoroughly mixed, coned and quartered on a precleaned floor. The ash was placed into four pre-proofed glass containers fitted with moisture tight lids.

Precipitator ash was collected from the plant ash conveyor system by placing a specially built container under the chain conveyor. When the container became full (10 - 20 minutes), it was replaced and the contents were emptied into a tared 200-L drum. Two tube-like samplers or "carrots" were inserted into the drum and a sample "cork" was extracted. At the completion of the run the sample cork was mixed, coned and quartered and placed in four pre-proofed glass containers with moisture type sealer lids.

A representative sample of the quench tank ash was scooped from a truck which was loaded with the ash from the ash pit. The sample was placed into a precleaned glass container.

All ash samples were preprocessed before being distributed for analyses, i.e,. shredded, milled, dried, or pulverized as required.

4.4 Flue Gas Sampling

4.4.1 Continuous Gas Monitors. Continuous stack gas monitoring was carried out on the exit side of the electrostatic precipitator to simultaneously measure the concentrations in the gaseous constituents of the following:

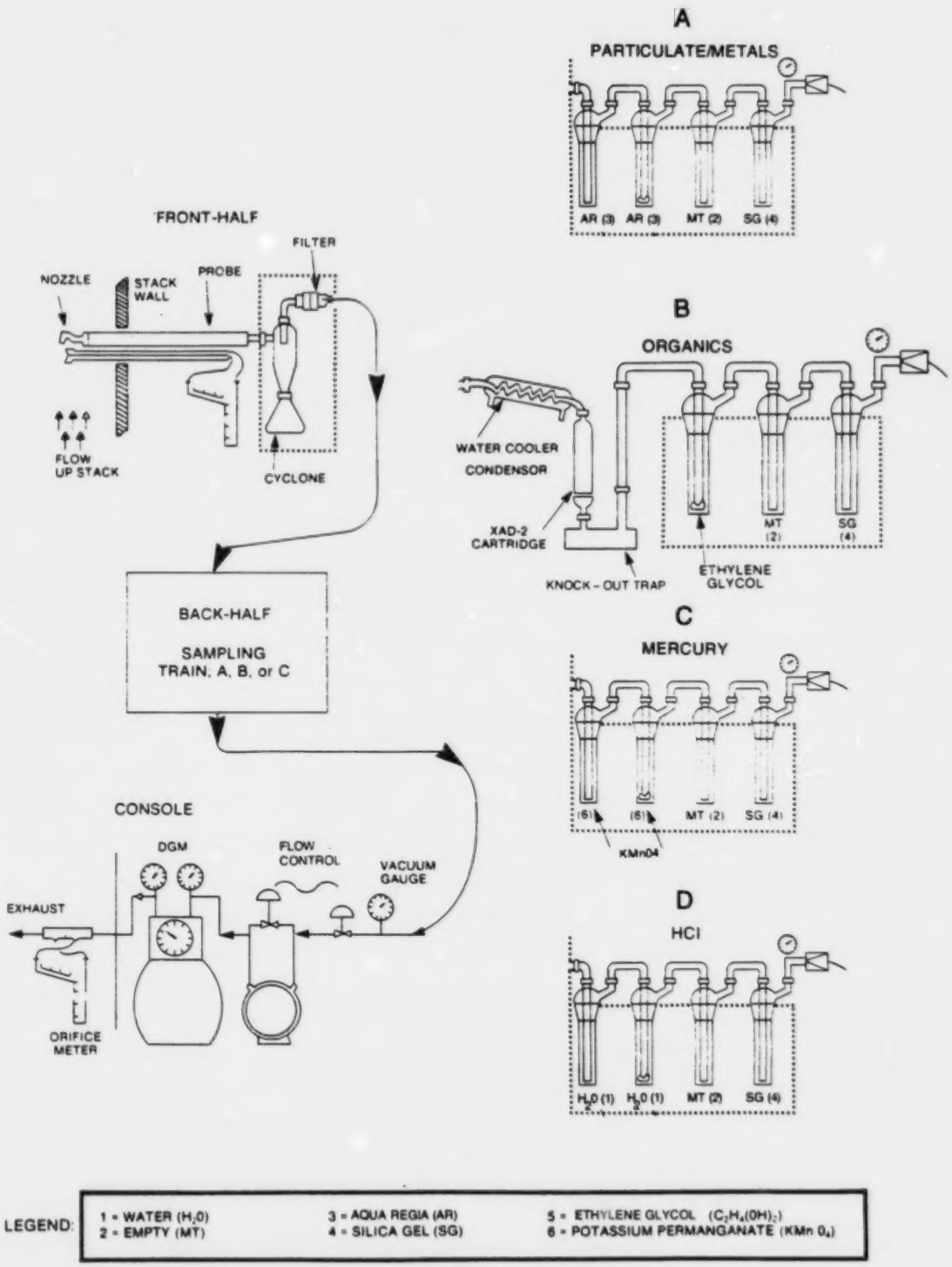
carbon monoxide (CO)	nitrogen oxides (NO_x)
carbon dioxide (CO_2)	hydrogen chloride (HCl)
oxygen (O_2)	total hydrocarbons (THC)
sulphur dioxide (SO_2)	(hot and cold)

A multipoint extraction system was designed and constructed based on the sampling point criteria in American Society for Testing and Materials (ASTM) Methodologies Procedure PT-10. The diversity of the analyzers required three independent conditioning systems for a) HCl; b) THC(hot); and c) multicomponent analysis (SO_2, NO_x, CO, CO_2, THC(cold) and O_2). Representative gas samples were extracted from the source, particulate matter removed and then further treatment to remove uncombined moisture was carried out depending upon the demands of the analyzer. The analyzers were calibrated using commercially available certified zero and span gases which had been verified by the best available reference methods. Calibration of each system was performed immediately before and at the conclusion of each test. Overall system checks were also performed to identify possible losses within the system by injecting gases at the analyzer inlet, conditioning system inlet, and the entrance to the heated sampling line.

4.4.2 Manual Sampling. Manual sampling trains were used to collect samples for metals/particulate, trace organics, mercury, particle size distribution and acid gases in the flue gas. Table 4.1 lists the gas sampling methodologies. With the exception of the particle size/acid gases train, samples were collected through four ports, and involved isokinetic sampling from multipoint traverses across the exhaust duct of unit 4. Traversing of all trains occurred simultaneously and each performance test was not less than four hours of actual testing time. Leak checks were conducted at the beginning and at the end of each traverse. Figure 4.1 presents a schematic of the sampling trains.

TABLE 4.1 EXHAUST GAS EMISSION MANUAL SAMPLING METHODOLOGIES

Sampling Parameter	Sampling Equipment and Protocol
Trace Organics - Dioxins, Furans, Polychlorinated biphenyls, Chlorophenols, Chlorobenzenes, Polycyclic aromatic hydrocarbons	Modified Method E train (ASME Draft 4, October 1984)
Mercury	Modified Method E train (4)
Particulate, Trace Metals, Major Metals	Modified Method E train (5)
Particle Size/Acid Gases	Cascade Impactor, Single point, in-stack and Method E train (4)



LEGEND:

1 = WATER (H_2O)	3 = AQUA REGIA (AR)	5 = ETHYLENE GLYCOL ($C_2H_4(OH)_2$)
2 = EMPTY (MT)	4 = SILICA GEL (SG)	6 = POTASSIUM PERMANGANATE ($KMnO_4$)

FIGURE 4.1 SCHEMATIC OF SAMPLING TRAINS

4.5 Analytical Protocols

All organic analyses were completed by Environment Canada's River Road Environmental Technology Centre. Diagnostic Research Laboratories completed the ultimate, proximate, higher heating value (HHV) and combustible analyses, and the Ontario Research Foundation performed the metals analyses. In most cases, standard methods were applied.

4.5.1 Metals. Samples for metal analyses were prepared in a manner compatible with the nature of the sample and the analysis required. The preparation procedure included digesting the samples with aqua regia followed by a concentration process and subsequent analyses. Trace metals were analyzed by direct current plasma (DCP) atomic emission spectroscopy. Atomic absorption spectroscopy was utilized for the determination of arsenic (As), antimony (Sb), selenium (Se) and tellurium (Te).

4.5.2 Organics. Six classes of organic compounds were targeted for analyses of refuse, ash and exhaust gas emission. These include: polychlorinated-dibenzo-p-dioxins (PCDD) and polychlorinated-dibenzo-furans (PCDF), polychlorinated biphenyls (PCB), chlorinated benzenes (CB), chlorinated phenols (CP) and polycyclic aromatic hydrocarbons (PAH).

The fundamental steps in processing and analysis of all organic samples consisted of:

a) spiking with surrogate standard solution,
b) solvent extraction of organic contaminants from the matrix,
c) clean-up of the raw extract to remove some of the co-extracted, non-target organics, and to separate target organics into four fractions for class-specific analysis,
d) instrumental analyses by gas chromatography/mass spectrometry (GC/MS) of each fraction, and
e) data interpretation and quantitation of target organic levels.

4.5.3 Miscellaneous. Table 4.2 summarizes the other analyses (i.e., ultimate, proximate, mercury, chloride, particle sizing, etc.) performed on collected samples, referencing the standard method followed and/or instrumental analyses performed.

4.5.4 Leachate. To evaluate the mobility of organic contaminants in ashes, a modified multiple sequential batch leaching procedure was employed. A distilled water leach at a 20:1 liquid-to-solid ratio was performed and repeated at higher ratios.

TABLE 4.2 SUMMARY OF ANALYTICAL METHODS

Parameter	Analytical Technique	Reference Method
Trace Organics	Gas chromatography/Mass spectrometry	Environment Canada/NITEP
Metals (Trace)	Plasma Atomic Emission spectroscopy	Environment Canada/NITEP
Antimony, Selenium, Tellurium, Arsenic, Tin	Atomic Absorption spectroscopy	Environment Canada/NITEP
Mercury	Flameless Cold Vapour-Atomic Absorption	Environment Canada/NITEP
Chloride (HCl)	Ion Chromatography	Environment Canada/NITEP
Particulate Loading	Gravimetric	Environment Canada (4)
Particle Sizing	Gravimetric	Environment Canada (4)
Sulphur	Tubidometric Technique	ASTM D3177
Calorific Value (Higher Heating Value)	Oxygen Bomb Calorimeter	ASTM D2015-77
Chlorine	Agentometric Nitration	ASTM D2361
Combustibles (loss on Ignition)	Muffle Furnace (750°C)	ASTM D3174-82
Volatile Matter	Muffle Furnace	ASTM D3175
Ash	Muffle Furnace	ASTM D3174
Carbon, Hydrogen	Leco Furnace Technique	ASTM D3178
Nitrogen	Leco Furnace and Kjeldahl	ASTM D3179
Moisture	Evaporation	ASTM E790

To determine the mobility of heavy metals in ashes, under non-aggressive leaching conditions, the multiple sequential batch leaching procedure was used. This method involved using a distilled water batch leach test at a 20:1 liquid-to-solid ratio and repeated for five cycles.

To estimate metal speciation in the ash, ashes were subjected to the sequential chemical extraction procedure. This procedure determines short- and long-term leachability of metals in ashes.

Finally, the acid neutralization capacity of each ash was determined using the ASTM procedure C400-64, with the following modification: 0.5 N nitric acid solution was used instead of 0.3 N sulphuric acid.

Heavy metal concentrations in both the ash and leachate were measured by inductively coupled argon plasma flame, atomic absorption or graphite furnace flame atomic absorbtion spectroscopy.

4.6 Quality Assurance and Quality Control

The broad program scope and large number of participants involved in the project team required considerable effort to ensure that a high level of quality control was maintained. The prime field contractor, Lavalin Inc., established its own internal quality assurance/quality control (QA/QC) program. In addition, the Ontario Ministry of the Environment (MOE), through a contract with Concord Scientific Corporation, established an independent external QA/QC program.

The findings of both the internal and external QA/QC programs indicated that the field study was executed properly, according to the stated sampling and analytical protocols, using properly calibrated and/or proofed equipment. Samples collected during this test program were deemed to be representative and the data reported was complete and accurate. To the best of the QA/QC auditors' knowledge, any errors, omissions and problems are correctly documented in the reports.

The results from the interlaboratory QA/QC program indicate that both organic and metal samples were analyzed by all laboratories within an acceptable degree of precision (metals - 30% relative standard deviation (RSD), and organics - 50% RSD) and accuracy (recoveries of > 70% and < 130%). The QA laboratories confirmed the results obtained by the main laboratories. However, poor interlaboratory comparisons were noted for arsenic, barium and chorophenols (uncorrected for spike recoveries) in both boiler and precipitator ashes.

5 PERFORMANCE TEST RESULTS

This chapter briefly summarizes the performance test (PT) results and the key findings. Based on the characterization test results, five operating conditions were selected for detailed performance testing. Thirteen of 15 performance tests were completed successfully as discussed in Chapter 3. The five operating modes selected for the performance test phase and the successfully completed PT runs are shown in Figure 5.1.

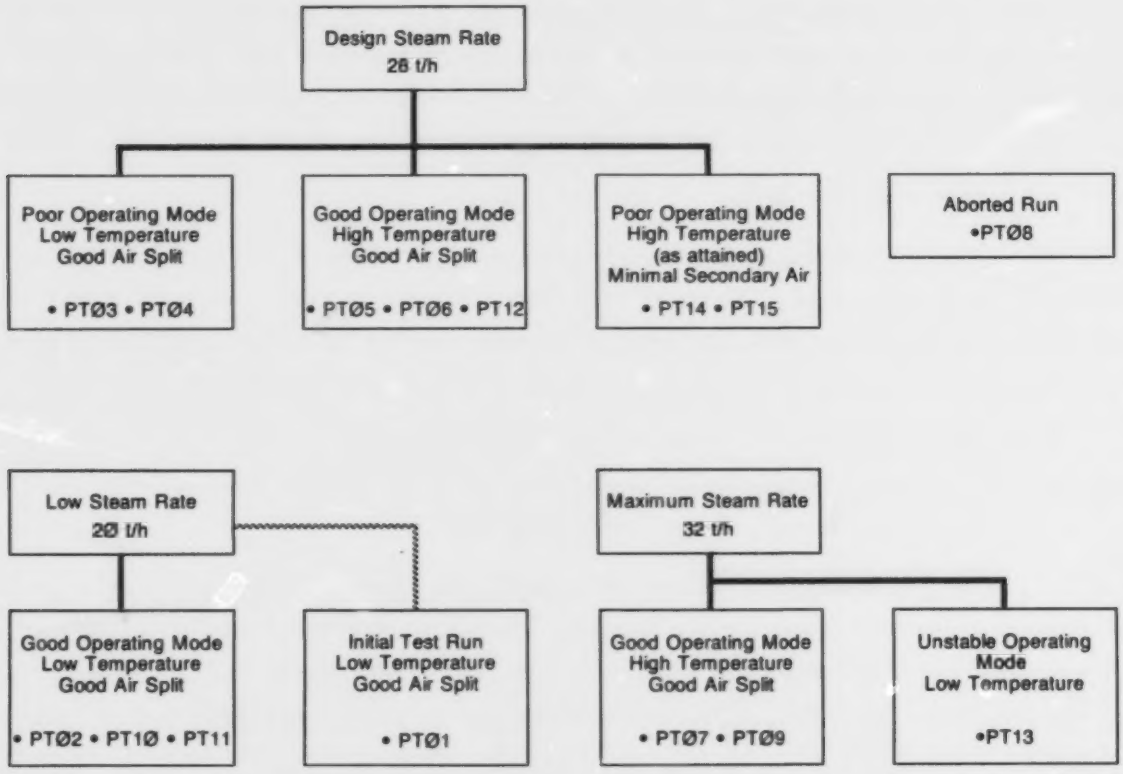


FIGURE 5.1 PERFORMANCE TEST PROGRAM INCINERATOR OPERATING MODES

5.1 Comparison of Test Data Within Groups

To determine whether each pair or triplet of tests within each of the groups in Figure 5.1 could be considered to represent, as an average, each particular test condition, a detailed review was made of the data for each test to identify similarities and

differences between tests within a group. Some of the more relevant results are summarized in Tables 5.1 and 5.2 for each successfully completed test and grouped by operating mode. Operating parameters such as steam rate, primary/secondary air ratio, radiation chamber temperature, boiler inlet temperature, excess air level and flue gas flow rate and composition were reviewed. Also, all continuous gas data and stack sampling train results for each test were reviewed within each group.

Based on this review, it became evident that one test run (PT-13) was not representative of the intended operating condition. Accordingly, as shown in Figure 5.1, PT-13 was set apart from PT-07 and -09. All other tests within each group were determined to be similar and representative of the intended operating condition. Accordingly, operating conditions and emissions are compared in the remainder of this report on a test group average basis. The results for each of the five performance test operating conditions are summarized in Figures 5.2 to 5.6.

5.2 Operating Conditions

Table 5.3 summarizes the key operating parameters for each of the five operating conditions. The incinerator was operated over a wide range of operating conditions. The key process parameters that were utilized to obtain the five distinct operating conditions covered a wide range of values on a group average basis as follows:

- steam rate ranged from 71% to 114% of the design rate,
- radiation chamber temperatures ranged from 859°C to 1046°C, and
- excess air levels ranged between 78% and 140%.

5.2.1 Good Operating Conditions at Design Steam Rate. This performance test condition was designed to represent a base case at steady performance with relatively low excess air (78%), a reasonable radiation chamber temperature (1012°C), a good primary/secondary air ratio (65:35), and a relatively low carbon monoxide concentration (28 ppm).

5.2.2 Poor Operating Conditions at Design Steam Rate. These poor operating modes were selected to determine the effect of temperature and air distribution (primary/secondary) on emissions. The poor operating conditions at the design rate involved relatively high excess air levels (130 and 113% respectively). These operating conditions produced relatively high carbon monoxide concentrations (78 ppm and 163 ppm respectively) compared to the good operating conditions (28 ppm). PT-03 and PT-04 had a low average radiation temperature (859°C); these conditions were designated "poor

TABLE 5.1 KEY PROCESS DATA PER PERFORMANCE TEST GROUPED BY OPERATING MODE

	Good Operation/ Low Rate			Good Operation/ Design Rate			Good Operation/ High Rate		High	Poor Operation/ Low Temperature		Poor Operation/ Poor Air	
	PT02	PT10	PT11	PT05	PT06	PT12	PT07	PT09	PT13	PT03	PT04	PT14	PT15
Steam Rate (tonnes/hour)	20.0	20.0	20.0	28.0	28.1	27.9	31.8	31.8	31.6	28.1	27.8	28.4	28.3
Refuse Feed Rate (wet tonne/h)	6.2	6.5	6.7	8.7	8.7	9.3	8.6	10.8	11.3	10.1	9.0	8.4	9.0
Steaming Ratio (tonnes steam/tonnes refuse)	3.2	3.1	3.0	3.2	3.2	3.0	3.7	2.9	2.8	2.8	3.1	3.4	3.1
Moisture in Refuse (%)	38.6	32.9	39.3	36.8	38.3	30.9	32.3	37.2	37.2	32.2	36.3	31.2	35.1
Moisture in Flue Gas (% VOL)	13.4	11.9	13.3	15.8	16.4	14.7	13.8	16.1	15.2	14.1	13.1	12.5	14.1
Combustion Efficiency (%)	99.99	99.98	99.98	99.98	99.98	99.97	99.96	99.96	99.94	99.94	99.93	99.87	99.86
Input/Output Efficiency (%)	62.4	60.5	62.0	67.3	60.5	63.3	67.9	64.4	58.8	60.5	59.7	64.8	61.8
Incinerator Ash Rate (dry kg/h)	1156	2365	1414	2311	2717	2210	1888	2324	2862	2749	2306	1797	2360
Percent Refuse Input (%)	18.6	36.4	21.1	26.6	31.2	23.7	22.0	21.5	25.3	27.2	25.6	21.4	26.3
Percent Combustibles (%)	4.0	3.3	0.6	1.5	11.9	4.1	7.5	2.8	14.6	2.3	6.0	1.9	6.4
Boiler Ash Rate (dry kg/h)	29.4	36.6	33.3	33.5	24.4	44.0	41.5	58.9	62.0	30.7	38.4	57.3	42.9
Percent Refuse Input (%)	0.5	0.6	0.5	0.4	0.3	0.5	0.5	0.5	0.5	0.3	0.4	0.7	0.5
Percent Combustibles (%)	5.9	5.9	2.3	15.5	7.2	1.3	21.9	23.7	1.3	10.0	10.1	3.0	5.3
Precipitator Ash Rate (dry kg/h)	46.0	46.6	43.5	47.0	54.2	71.0	65.8	92.4	128.4	131.6	131.0	121.8	110.8
Percent Refuse Input (%)	0.7	0.7	0.6	0.5	0.6	0.8	0.8	0.9	1.1	1.3	1.5	1.5	1.2
Percent Combustibles (%)	7.2	4.8	8.6	8.0	36.9	7.1	11.8	9.4	7.4	5.8	6.3	10.5	6.0
Flue Gas Flow (Avg 3 Trains) (Sm^3/min)	874	910	875	828	844	953	945	985	1036	1130	1156	1055	1046
Total Comb. Air (Bailey) (Am^3/min)	477	553	498	546	541	550	625	750	725	918	960	540	555
Combustion Air Distribution:													
- Primary/Secondary Ratio	58:42	53:47	63:37	65:35	64:36	66:34	49:51	60:40	63:37	61:39	61:39	88:12	89:11
- Secondary Front/Rear Ratio	42:58	56:44	44:56	39:61	31:69	42:58	60:40	64:36	64:36	47:53	50:50	27:73	25:75
Temperatures (°C):													
- Lower Radiation Chamber (F/R avg)	849	875	869	1014	1030	992	1085	1006	997	861	856	992	964
- Upper Radiation Chamber (F/R avg)	637	688	688	777	774	793	839	791	799	672	655	747	718
- Boiler Inlet	712	688	689	813	817	785	836	809	769	724	700	745	762
- Stack	199	212	212	206	212	225	220	233	240	229	232	232	228

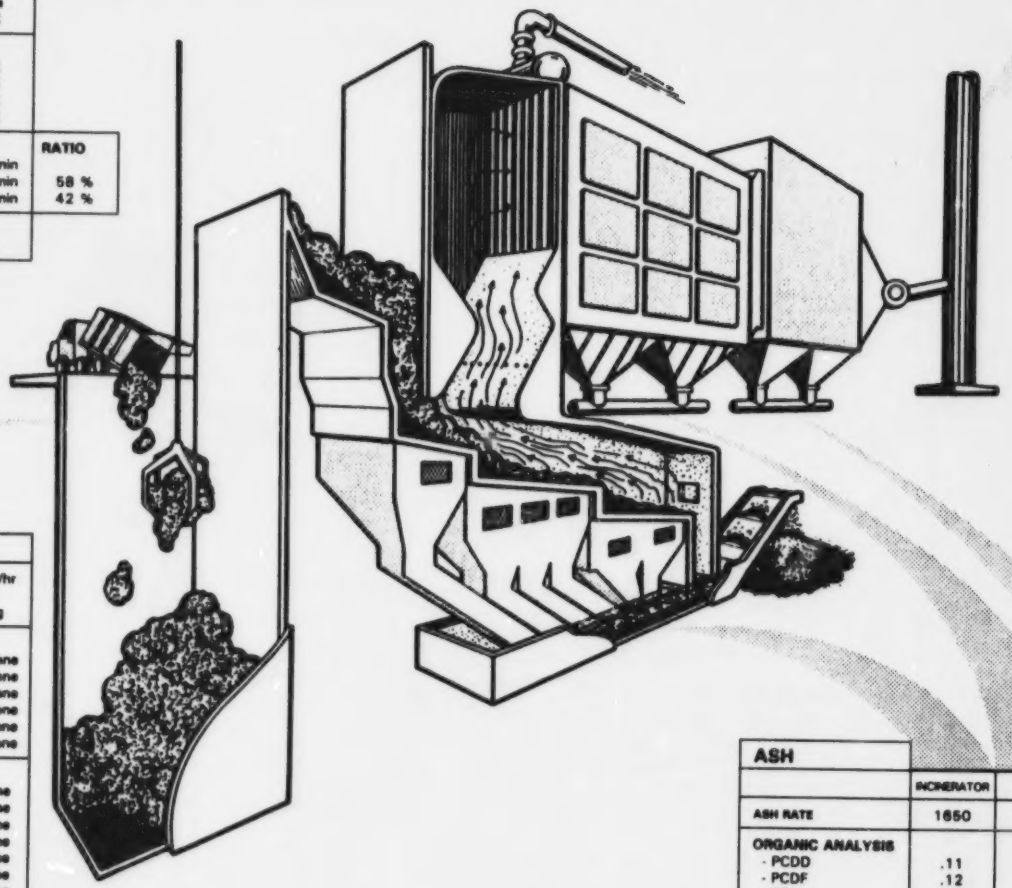
TABLE 5.2 KEY EMISSION DATA PER PERFORMANCE TEST GROUPED BY OPERATING MODE

	Good Operation/ Low Rate			Good Operation/ Design Rate			Good Operation/ High Rate		High	Poor Operation/ Low Temperature		Poor Operation/ Poor Air	
	PT02	PT10	PT11	PT05	PT06	PT12	PT07	PT09	PT13	PT03	PT04	PT14	PT15
Continuous Flue Gas Data (corr. to 12% CO_2):													
Carbon dioxide (%)	8	8	8	11	11	9	10	11	10	9	8	8	9
Carbon monoxide (ppm)	17	24	30	20	27	37	43	43	77	76	80	153	173
Oxygen (dry basis) (%)	13	13	12	9	9	10	10	10	10	12	12	12	11
Total hydrocarbons (cold) (ppm)	2	3	2	1	2	2	2	2	2	2	2	3	3
Total hydrocarbons (hot) (ppm)	6	4	5	NA	NA	4	NA	NA	NA	3	6	NA	2
Sulphur dioxide (ppm)	160	209	175	178	186	225	192	128	178	145	160	162	151
Nitrogen oxides (ppm)	232	191	192	172	169	199	186	202	205	224	246	191	183
Hydrogen chloride (ppm)	565	465	466	504	366	487	512	369	500	NA	453	594	447
Excess Air (%)	143	152	126	69	75	91	84	84	92	128	132	116	110
Opacity (%)	26	31	30	32	29	39	35	30	36	35	36	36	35
Particulate Sampling Train													
- Concentration @ 12% CO_2 (mg/Sm^3)	23.7	28.9	26.3	15.8	20.5	30.7	35.3	35.9	53.7	68.1	41.7	72.9	52.0
- Emission Rate/Refuse Ratio (kg/tonne)	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.2	0.4	0.3
Hydrogen Chloride Sampling Train													
- Concentration @ 12% CO_2 (ppm)	612	463	440	327	312	450	364	397	449	601	327	398	398
- Emission Rate/Refuse Ratio (kg/tonne)	5.4	4.3	3.8	3.0	2.9	3.7	3.4	3.3	3.7	5.0	3.2	4.2	3.9
Total PCDD (Organic Sampling Train)													
- Concentration @ 12% CO_2 (ng/Sm^3)	105	29	24	13	11	33	45	65	164	302	295	205	233
- Emission Rate/Refuse Ratio (µg/tonne)	559	151	122	68	59	154	256	312	736	1444	1486	1065	1195
Total PCDF (Organic Sampling Train)													
- Concentration @ 12% CO_2 (ng/Sm^3)	179	81	84	49	32	52	101	100	118	287	310	336	277
- Emission Rate/Refuse Ratio (µg/tonne)	950	429	423	261	171	247	570	480	532	1369	1565	1747	1421

OPERATING CONDITIONS			
STEAM			
- FLOW	20	tonne/h	
- PRESSSURE	4300	kPa	
- TEMPERATURE	320	°C	
TEMPERATURES			
- LOWER INCINERATOR	860	°C	
- UPPER INCINERATOR	670	°C	
- BOILER INLET	700	°C	
- COMBUSTION AIR	32	°C	
AIR FLOW			**RATIO**
- COMBUSTION	510	Am³/min	
- PRIMARY	300	Am³/min	58 %
- SECONDARY	210	Am³/min	42 %
EFFICIENCY			
- INPUT/OUTPUT	61.6	%	

STACK EMISSIONS		
GAS		
- FLOW	890	Sm³/min
- TEMPERATURE	210	°C
- MOISTURE	12.9	%
- OPACITY	29.0	%
CONTINUOUS DATA		
- O_2	13	%
- CO_2	8	%
- CO	23	ppm
- NO_x	200	ppm
- SO_2	180	ppm
- THC	2	ppm
ACID GAS		
- HCl	500	ppm
ORGANIC ANALYSIS		
- PCDD	53	ng/Sm³*
- PCDF	114	ng/Sm³*
- PCB	4280	ng/Sm³*
- PAH	7090	ng/Sm³*
- CB	3500	ng/Sm³*
- CP	9490	ng/Sm³*
PARTICULATE	26	mg/Sm³*
METALS		
- Cd	26	ug/Sm³*
- Pb	980	ug/Sm³*
- Cr	11	ug/Sm³*
- Ni	9	ug/Sm³*
- Hg	780	ug/Sm³*
- Sb	35	ug/Sm³*
- As	2	ug/Sm³*
- Cu	39	ug/Sm³*
- Zn	1620	ug/Sm³*

* *Corrected to 12% CO_2*

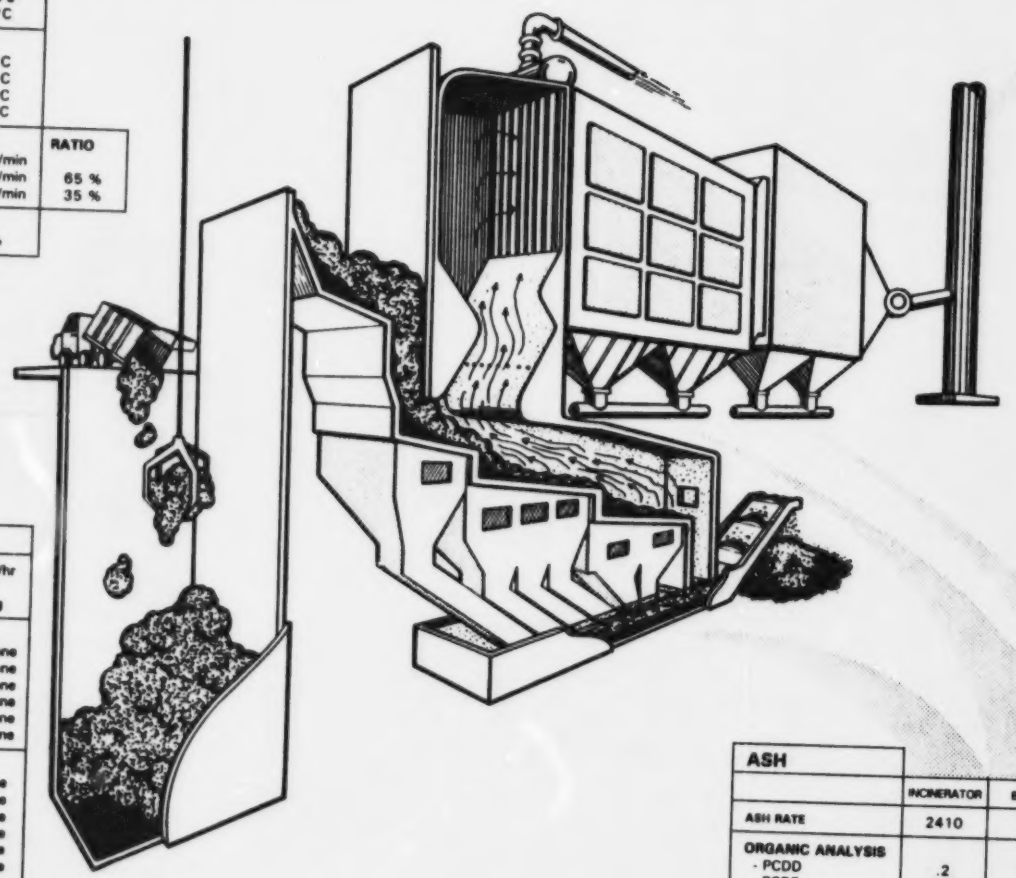


REFUSE		
FEED RATE	6.5	tonne/hr
MOISTURE	37	%
CALORIFIC VALUE	2910	cal/g
ORGANIC ANALYSIS		
- PCDD	7.8	mg/tonne
- PCDF	ND	mg/tonne
- PCB	55	mg/tonne
- PAH	4720	mg/tonne
- CB	22	mg/tonne
- CP	810	mg/tonne
METALS		
- Cd	2.9	g/tonne
- Pb	120	g/tonne
- Cr	53	g/tonne
- Ni	23	g/tonne
- Hg	.58	g/tonne
- Sb	2.9	g/tonne
- As	1.0	g/tonne
- Cu	390	g/tonne
- Zn	190	g/tonne

ASH				
	INCINERATOR	BOILER	PRECIPITATOR	
ASH RATE	1650	33	45	Kg/h
ORGANIC ANALYSIS				
- PCDD	.11	140	760	ng/g
- PCDF	.12	120	220	ng/g
- PCB	ND	ND	5	ng/g
- PAH	150	70	100	ng/g
- CB	16	1570	960	ng/g
- CP	10	110	1240	ng/g
METALS				
- Cd	3.4	290	880	ug/g
- Pb	770	9300	20700	ug/g
- Cr	230	330	450	ug/g
- Ni	100	110	100	ug/g
- Hg	0.003	8.3	49	ug/g
- Sb	12	340	550	ug/g
- As	7.7	83	130	ug/g
- Cu	1770	640	1320	ug/g
- Zn	2310	17600	60900	ug/g

FIGURE 5.2
GOOD OPERATING CONDITIONS, LOW BURNING RATE
PERFORMANCE TEST SUMMARY - PT02/10/11

OPERATING CONDITIONS			
STEAM			
- FLOW	28	tonne/h	
- PRESSSURE	4300	kPa	
- TEMPERATURE	320	°C	
TEMPERATURES			
- LOWER INCINERATOR	1010	°C	
- UPPER INCINERATOR	780	°C	
- BOILER INLET	810	°C	
- COMBUSTION AIR	34	°C	
AIR FLOW			**RATIO**
- COMBUSTION	550	Am³/min	
- PRIMARY	360	Am³/min	65 %
- SECONDARY	190	Am³/min	35 %
EFFICIENCY			
- INPUT/OUTPUT	63.7	%	



STACK EMISSIONS		
GAS		
- FLOW	880	Sm^3/min
- TEMPERATURE	210	°C
- MOISTURE	15.7	%
- OPACITY	33.3	%
CONTINUOUS DATA		
- O_2	9	%
- CO_2	10	%
- CO	28	ppm
- NO_x	180	ppm
- SO_2	200	ppm
- THC	2	ppm
ACID GAS		
- HCl	450	ppm
ORGANIC ANALYSIS		
- PCDD	19	ng/Sm^{3*}
- PCDF	44	ng/Sm^{3*}
- PCB	3020	ng/Sm^{3*}
- PAH	4030	ng/Sm^{3*}
- CB	3300	ng/Sm^{3*}
- CP	5080	ng/Sm^{3*}
PARTICULATE	22	mg/Sm^{3*}
METALS		
- Cd	24	ug/Sm^{3*}
- Pb	670	ug/Sm^{3*}
- Cr	7	ug/Sm^{3*}
- Ni	5	ug/Sm^{3*}
- Hg	700	ug/Sm^{3*}
- Sb	36	ug/Sm^{3*}
- As	3	ug/Sm^{3*}
- Cu	33	ug/Sm^{3*}
- Zn	1130	ug/Sm^{3*}

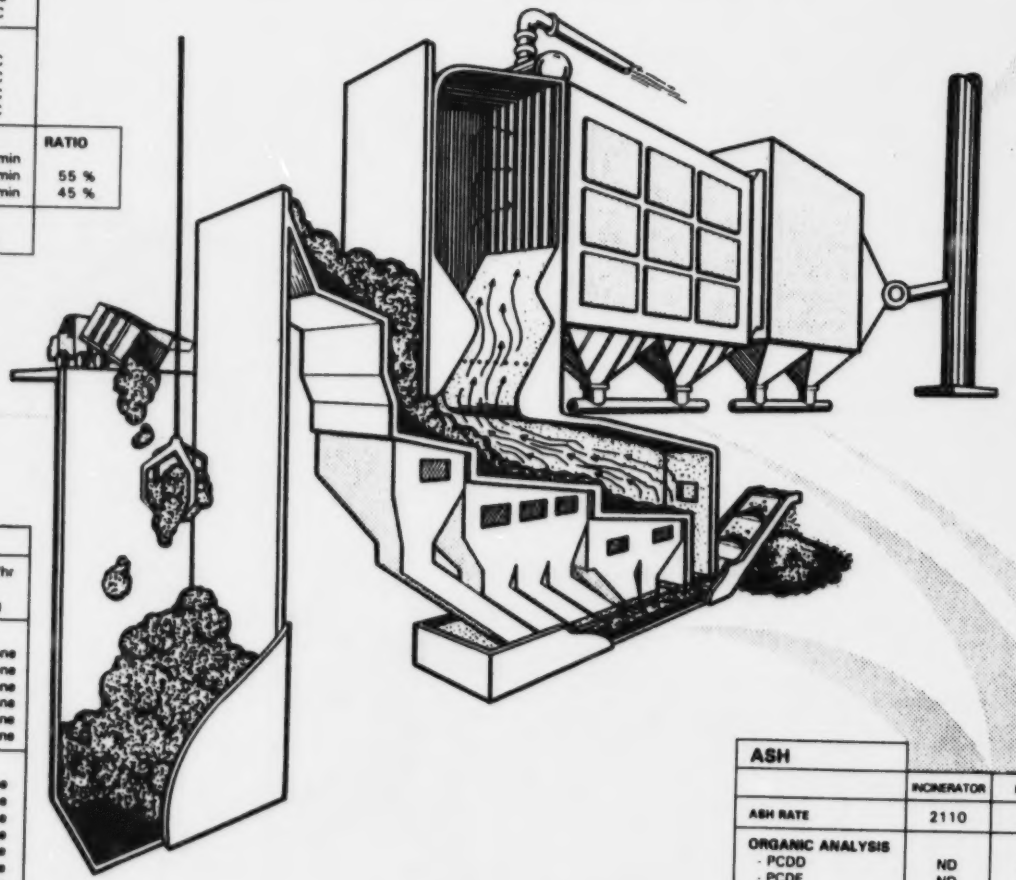
* *Corrected to 12% CO_2*

REFUSE		
FEED RATE	8.9	tonne/hr
MOISTURE	35	%
CALORIFIC VALUE	2860	cal/g
ORGANIC ANALYSIS		
- PCDD	32	mg/tonne
- PCDF	3.2	mg/tonne
- PCB	45	mg/tonne
- PAH	1660	mg/tonne
- CB	72	mg/tonne
- CP	1570	mg/tonne
METALS		
- Cd	6.0	g/tonne
- Pb	660	g/tonne
- Cr	200	g/tonne
- Ni	27	g/tonne
- Hg	.62	g/tonne
- Sb	2.2	g/tonne
- As	1.3	g/tonne
- Cu	250	g/tonne
- Zn	220	g/tonne

ASH				
	INCINERATOR	**BOILER**	**PRECIPITATOR**	
ASH RATE	2410	34	57	Kg/h
ORGANIC ANALYSIS				
- PCDD	.2	37	580	ng/g
- PCDF	1.0	31	190	ng/g
- PCB	ND	ND	ND	ng/g
- PAH	540	25	110	ng/g
- CB	45	360	890	ng/g
- CP	16	80	1820	ng/g
METALS				
- Cd	4	210	1060	ug/g
- Pb	1760	7480	21100	ug/g
- Cr	250	300	480	ug/g
- Ni	130	120	110	ug/g
- Hg	0.03	7	72	ug/g
- Sb	16	330	750	ug/g
- As	7	91	170	ug/g
- Cu	2540	530	1480	ug/g
- Zn	1780	17400	60700	ug/g

FIGURE 5.3
GOOD OPERATING CONDITIONS, DESIGN BURNING RATE
PERFORMANCE TEST SUMMARY - PT05/06/12

OPERATING CONDITIONS			
STEAM			
- FLOW	31.8	tonne/h	
- PRESSSURE	4400	kPa	
- TEMPERATURE	320	°C	
TEMPERATURES			
- LOWER INCINERATOR	1040	°C	
- UPPER INCINERATOR	820	°C	
- BOILER INLET	820	°C	
- COMBUSTION AIR	28	°C	
AIR FLOW			RATIO
- COMBUSTION	690	Am³/min	
- PRIMARY	380	Am³/min	55 %
- SECONDARY	310	Am³/min	45 %
EFFICIENCY			
- INPUT/OUTPUT	66.2	%	



STACK EMISSIONS		
GAS		
- FLOW	985	Sm³/min
- TEMPERATURE	226	°C
- MOISTURE	14.9	%
- OPACITY	33	%
CONTINUOUS DATA		
- O_2	10	%
- CO_2	10	%
- CO	43	ppm
- NO_x	190	ppm
- SO_2	160	ppm
- THC	2	ppm
ACID GAS		
- HCl	440	ppm
ORGANIC ANALYSIS		
- PCDD	55	ng/Sm³*
- PCDF	100	ng/Sm³*
- PCB	4840	ng/Sm³*
- PAH	5380	ng/Sm³*
- CB	4320	ng/Sm³*
- CP	7990	ng/Sm³*
PARTICULATE	36	mg/Sm³*
METALS		
- Cd	41	ug/Sm³*
- Pb	1600	ug/Sm³*
- Cr	15	ug/Sm³*
- Ni	8	ug/Sm³*
- Hg	870	ug/Sm³*
- Sb	44	ug/Sm³*
- As	5	ug/Sm³*
- Cu	54	ug/Sm³*
- Zn	2060	ug/Sm³*

** Corrected to 12% CO_2*

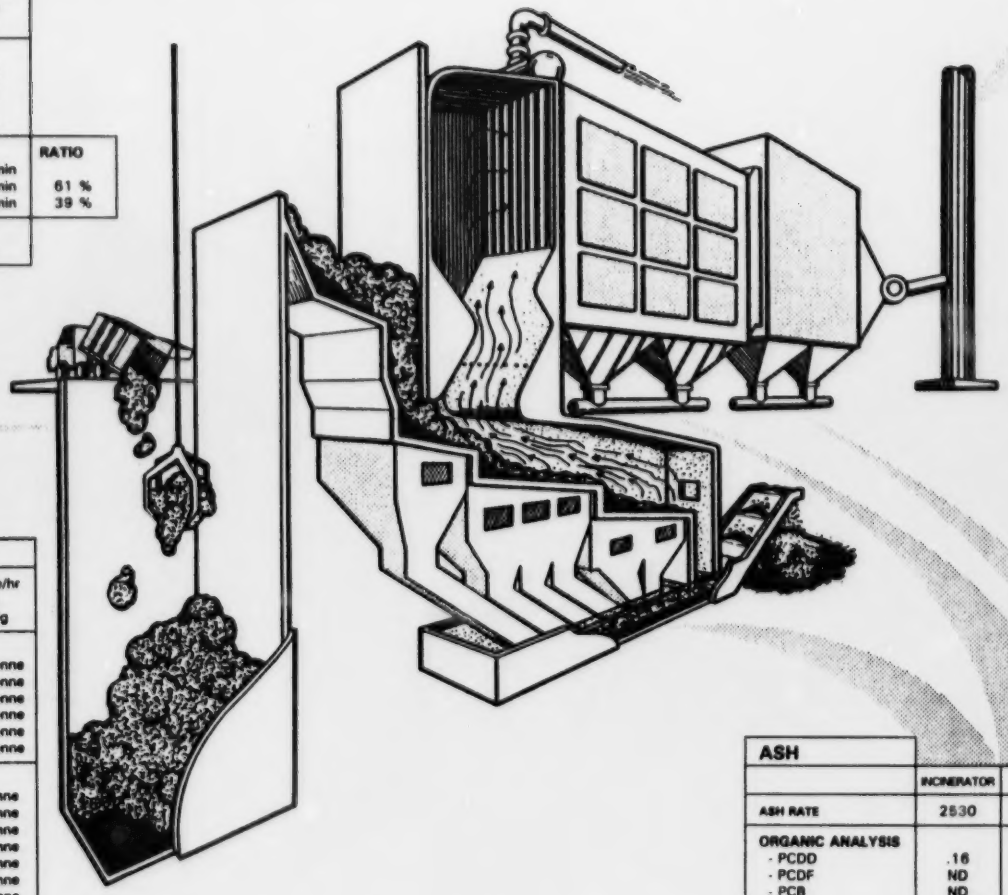
REFUSE		
FEED RATE	9.7	tonne/hr
MOISTURE	35	%
CALORIFIC VALUE	2890	cal/g
ORGANIC ANALYSIS		
- PCDD	15	mg/tonne
- PCDF	.05	mg/tonne
- PCB	69	mg/tonne
- PAH	10400	mg/tonne
- CB	23	mg/tonne
- CP	2060	mg/tonne
METALS		
- Cd	6.7	g/tonne
- Pb	200	g/tonne
- Cr	60	g/tonne
- Ni	19	g/tonne
- Hg	.36	g/tonne
- Sb	5.4	g/tonne
- As	.6	g/tonne
- Cu	48	g/tonne
- Zn	330	g/tonne

ASH				
	INCINERATOR	BOILER	PRECIPITATOR	
ASH RATE	2110	50	79	Kg/h
ORGANIC ANALYSIS				
- PCDD	ND	23	620	ng/g
- PCDF	ND	26	280	ng/g
- PCB	ND	ND	ND	ng/g
- PAH	500	21	100	ng/g
- CB	4	530	1660	ng/g
- CP	20	100	1700	ng/g
METALS				
- Cd	3	150	760	g/g
- Pb	870	6640	17200	ug/g
- Cr	360	340	520	ug/g
- Ni	430	100	120	ug/g
- Hg	.04	6	73	ug/g
- Sb	9	270	530	ug/g
- As	8	74	130	ug/g
- Cu	4510	480	1300	ug/g
- Zn	1530	15600	44800	ug/g

FIGURE 5.4
GOOD OPERATING CONDITIONS, HIGH BURNING RATE
PERFORMANCE TEST SUMMARY - PT07/09

OPERATING CONDITIONS			
STEAM			
- FLOW	28	tonne/h	
- PRESSSURE	4300	kPa	
- TEMPERATURE	320	°C	
TEMPERATURES			
- LOWER INCINERATOR	860	°C	
- UPPER INCINERATOR	660	°C	
- BOILER INLET	710	°C	
- COMBUSTION AIR	34	°C	
AIR FLOW			**RATIO**
- COMBUSTION	940	Am³/min	
- PRIMARY	570	Am³/min	61 %
- SECONDARY	370	Am³/min	39 %
EFFICIENCY			
- INPUT/OUTPUT	60.1	%	

REFUSE		
FEED RATE	9.5	tonne/hr
MOISTURE	34	%
CALORIFIC VALUE	2820	cal/g
ORGANIC ANALYSIS		
- PCDD	67	mg/tonne
- PCDF	4.1	mg/tonne
- PCB	120	mg/tonne
- PAH	1730	mg/tonne
- CB	93	mg/tonne
- CP	1830	mg/tonne
METALS		
- Cd	5.9	g/tonne
- Pb	760	g/tonne
- Cr	89	g/tonne
- Ni	24	g/tonne
- Hg	1.1	g/tonne
- Sb	43	g/tonne
- As	1.4	g/tonne
- Cu	43	g/tonne
- Zn	190	g/tonne



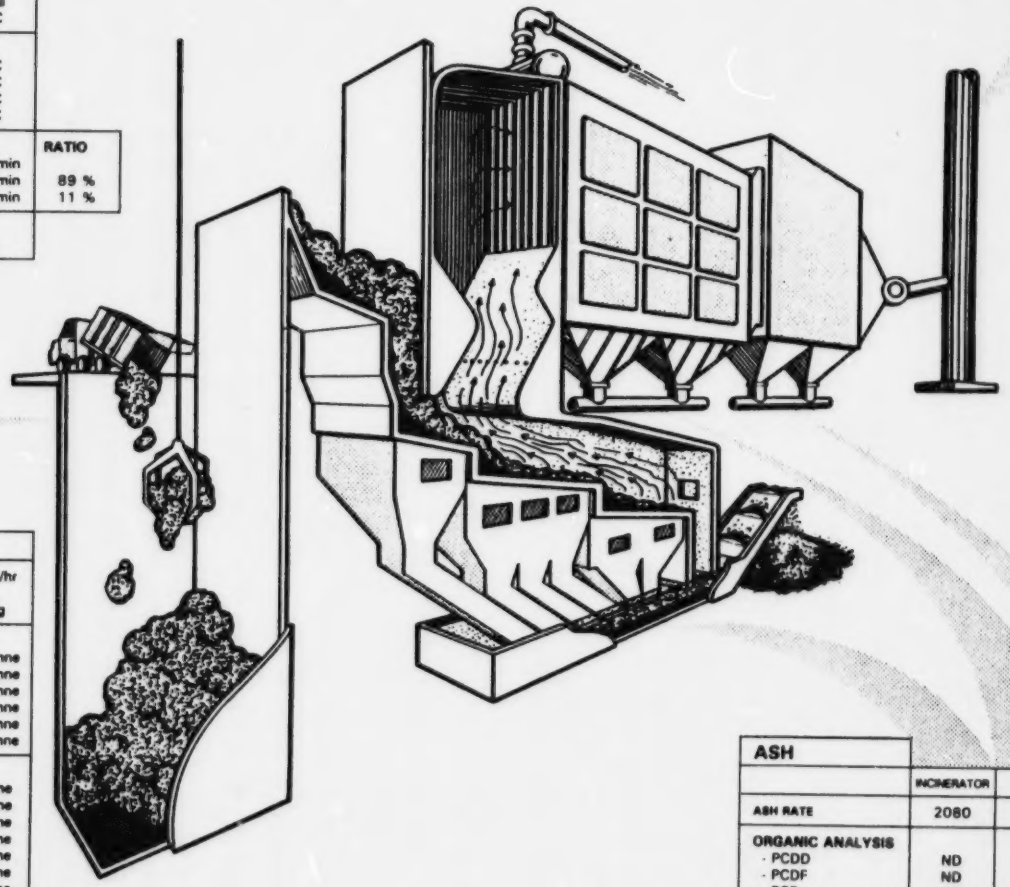
STACK EMISSIONS		
GAS		
- FLOW	1140	Sm³/min
- TEMPERATURE	230	°C
- MOISTURE	13.6	%
- OPACITY	35	%
CONTINUOUS DATA		
- O_2	12	%
- CO_2	8	%
- CO	78	ppm
- NO_x	240	ppm
- SO_2	150	ppm
- THC	2	ppm
ACID GAS		
- HCl	450	ppm
ORGANIC ANALYSIS		
- PCDD	300	ng/Sm³*
- PCDF	300	ng/Sm³*
- PCB	7000	ng/Sm³*
- PAH	21800	ng/Sm³*
- CB	9920	ng/Sm³*
- CP	22500	ng/Sm³*
PARTICULATE	55	mg/Sm³*
METALS		
- Cd	90	ug/Sm³*
- Pb	2040	ug/Sm³*
- Cr	21	ug/Sm³*
- Ni	8	ug/Sm³*
- Hg	810	ug/Sm³*
- Sb	112	ug/Sm³*
- As	6	ug/Sm³*
- Cu	91	ug/Sm³*
- Zn	5120	ug/Sm³*

* *Corrected to 12% CO_2*

ASH				
	INCINERATOR	BOILER	PRECIPITATOR	
ASH RATE	2530	34	130	Kg/h
ORGANIC ANALYSIS				
- PCDD	.16	43	600	ng/g
- PCDF	ND	25	230	ng/g
- PCB	ND	ND	12	ng/g
- PAH	160	33	120	ng/g
- CB	5	310	1380	ng/g
- CP	ND	68	1290	ng/g
METALS				
- Cd	4	140	510	ug/g
- Pb	1320	5510	10800	ug/g
- Cr	230	320	530	ug/g
- Ni	90	110	98	ug/g
- Hg	0.009	4	32	ug/g
- Sb	26	96	730	ug/g
- As	7	45	67	ug/g
- Cu	2240	540	950	ug/g
- Zn	2550	11100	33800	ug/g

FIGURE 5.5
POOR OPERATING CONDITIONS, DESIGN BURNING RATE, LOW TEMPERATURE
PEFORMANCE TEST SUMMARY - PT03/04

OPERATING CONDITIONS			
STEAM			
- FLOW	28	tonne/h	
- PRESSSURE	4300	kPa	
- TEMPERATURE	320	°C	
TEMPERATURES			
- LOWER INCINERATOR	980	°C	
- UPPER INCINERATOR	730	°C	
- BOILER INLET	750	°C	
- COMBUSTION AIR	32	°C	
AIR FLOW			RATIO
- COMBUSTION	550	Am³/min	
- PRIMARY	490	Am³/min	89 %
- SECONDARY	60	Am³/min	11 %
EFFICIENCY			
- INPUT/OUTPUT	63.3	%	



REFUSE		
FEED RATE	8.7	tonne/hr
MOISTURE	33.2	%
CALORIFIC VALUE	2980	cal/g
ORGANIC ANALYSIS		
- PCDD	23	mg/tonne
- PCDF	1.0	mg/tonne
- PCB	77	mg/tonne
- PAH	2810	mg/tonne
- CB	25	mg/tonne
- CP	800	mg/tonne
METALS		
- Cd	2.0	g/tonne
- Pb	380	g/tonne
- Cr	51	g/tonne
- Ni	28	g/tonne
- Hg	.95	g/tonne
- Sb	9	g/tonne
- As	1.4	g/tonne
- Cu	600	g/tonne
- Zn	280	g/tonne

STACK EMISSIONS		
GAS		
- FLOW	1050	Sm³/min
- TEMPERATURE	230	°C
- MOISTURE	13.3	%
- OPACITY	35	%
CONTINUOUS DATA		
- O_2	11	%
- CO_2	9	%
- CO	160	ppm
- NO_x	190	ppm
- SO_2	160	ppm
- THC	3	ppm
ACID GAS		
- HCl	520	ppm
ORGANIC ANALYSIS		
- PCDD	220	ng/Sm³*
- PCDF	310	ng/Sm³*
- PCB	1630	ng/Sm³*
- PAH	3150	ng/Sm³*
- CB	9520	ng/Sm³*
- CP	23700	ng/Sm³*
PARTICULATE	62	mg/Sm³*
METALS		
- Cd	76	ug/Sm³*
- Pb	2500	ug/Sm³*
- Cr	14	ug/Sm³*
- Ni	7	ug/Sm³*
- Hg	620	ug/Sm³*
- Sb	86	ug/Sm³*
- As	6	ug/Sm³*
- Cu	89	ug/Sm³*
- Zn	3430	ug/Sm³*

* *Corrected to 12% CO_2*

ASH				
	INCINERATOR	BOILER	PRECIPITATOR	
ASH RATE	2080	50	116	Kg/h
ORGANIC ANALYSIS				
- PCDD	ND	51	950	ng/g
- PCDF	ND	17	260	ng/g
- PCB	ND	ND	24	ng/g
- PAH	320	69	330	ng/g
- CB	4	259	1520	ng/g
- CP	11	59	2970	ng/g
METALS				
- Cd	4	210	480	ug/g
- Pb	1640	8660	11800	ug/g
- Cr	170	240	350	ug/g
- Ni	72	110	110	ug/g
- Hg	.004	3	41	ug/g
- Sb	10	260	330	ug/g
- As	8	54	46	ug/g
- Cu	1310	530	930	ug/g
- Zn	1170	12800	27300	ug/g

FIGURE 5.6
POOR OPERATING CONDITIONS, DESIGN BURNING RATE,
POOR AIR DISTRIBUTION
PERFORMANCE TEST SUMMARY - PT14/15

TABLE 5.3 KEY PROCESS PARAMETERS PER PERFORMANCE TEST MODE

	Good Conditions/ Burning Rate			Poor Conditions/ Design Burn Rate	
	Low	Design	High	Low Temp.	Poor Dist.
Steam Rate (t/h)	20.0	28.0	31.8	28.0	28.4
Primary Air (% of total)	58	65	55	61	89
Secondary Air (% of total)	42	35	45	39	11
Radiation Chamber Temp. (°C)	864	1012	1046	859	978
Boiler Inlet Temperature (°C)	696	805	823	712	754
Excess Air Level (%)	140	78	84	130	113
Input/Output Efficiency (%)	61.6	63.7	66.2	60.1	63.3
Steaming Ratio (kg steam/kg refuse)	3.1	3.1	3.3	3.0	3.3
Flue Gas Flow Rate (Sm^3/min)	886	875	965	1143	1051

conditions at low temperature". The other poor operating conditions, represented by PT-14 and PT-15, represent a poor combustion air distribution (i.e., most combustion air under the grate, only 11% overfire air).

5.2.3 High and Low Steam Rates. High (32 t/h) and low (20 t/h) steam rates with good operating conditions were selected for comparison with the base case (28 t/h) to determine the effect on emissions. The low feed rate operating mode (20 t/h) was characterized by a good primary/secondary air ratio (58:42), a relatively low radiation chamber temperature (864°C), a high excess air level (140%), and relatively low average carbon monoxide concentration (24 ppm). The lower temperature and higher excess air level, compared to the design rate, demonstrate operation of the incinerator at a low rate.

The high feed rate condition (32 t/h) had a good primary/secondary air ratio (55:45), a relatively high radiation chamber temperature (1046°C), a low excess air level (84%), and a low average carbon monoxide concentration (43 ppm). The temperature, excess air level and carbon monoxide concentration simulate operation at a high rate compared to the design rate.

5.3 Continuous Gas Data

Table 5.4 summarizes the continuous gas monitoring results. The lowest carbon monoxide group average (24 ppm) occurred during the low rate tests while the highest (163 ppm) occurred during the poor air distribution tests. Typically, carbon monoxide levels below 250 ppm represent reasonable combustion efficiency, although modern facilities can be expected to achieve carbon monoxide levels of 50 ppm on average. Only the poor distribution operating condition experienced relatively high average levels of carbon monoxide (i.e., over 50 ppm). In setting up the various operating conditions, carbon monoxide was used as one of the primary indicators of the type of operation that was being achieved, both on a short-term basis and on a test average basis.

TABLE 5.4 CONTINUOUS GAS MONITORING RESULTS PER PERFORMANCE TEST MODE

	Good Conditions/ Burning Rate			Poor Conditions/ Design Burn Rate	
	Low	Design	High	Low Temp.	Poor Dist.
Carbon monoxide (ppm)	23.5	27.9	43	78.0	163.4
Total hydrocarbons					
cold (ppm)	2.3	1.8	1.7	2.1	3.1
hot (ppm)	5.1	N/A	N/A	4.3	N/A
Nitrogen oxides (ppm)	205	180	194	235	187
Hydrogen chloride (ppm)	499	452	441	N/A	521
Sulphur oxides (ppm)	181	196	160	153	157
Opacity (%)	29	33	32	35	35

Note: Values corrected to 12% carbon dioxide.

Total hydrocarbons showed little variation between test groups, with concentrations generally between 2 to 5 ppm. For modern incinerator facilities, hydrocarbon concentrations below 50 ppm are anticipated; levels below 10 ppm are now considered common.

Group averages for **nitrogen oxides** and **sulphur oxides** varied little between testing modes, as anticipated. The maximum group average of 235 ppm for nitrogen oxides and 196 ppm for sulphur dioxide was approximately 30% greater than the minimum (180 pm for NO_x and 153 ppm for SO_2) in both cases.

Hydrogen chloride group averages as measured by the continuous hydrogen chloride monitor were consistent between test groups. The maximum group average (521 ppm) was 18% above the minimum (452 ppm). Individual test results showed a more significant variation (i.e. 366 ppm to 594 ppm). Hydrogen chloride emissions were typical of uncontrolled emissions from municipal solid waste incinerators.

Operation of the opacity meter was suspect, since opacity readings did not relate adequately with particulate concentrations.

5.4 Trace Organic Emissions

Stack sampling train results for trace organic emissions are summarized in Table 5.5 and each of the main groups are discussed below.

TABLE 5.5 TRACE ORGANIC EMISSIONS PER PERFORMANCE TEST MODE

	Good Conditions/ Burning Rate			Poor Conditions/ Design Burn Rate	
	Low	Design	High	Low Temp.	Poor Dist.
Dioxins (ng/Sm^3)	52.6	18.8	55.4	298.5	218.9
Furans (ng/Sm^3)	114.5	44.5	100.7	298.3	306.4
Chlorophenols ($\mu g/Sm^3$)	9.5	5.1	8.0	22.5	23.7
PAHs ($\mu g/Sm^3$)	7.1	4.0	5.4	21.9	3.2
Chlorobenzene ($\mu g/Sm^3$)	3.5	3.3	4.4	9.9	9.5
PCBs ($\mu g/Sm^3$)	4.3	3.0	4.9	7.0	1.7

Note: Values corrected to 12% carbon dioxide.

5.4.1 Dioxins and Furans. Test data available on the old furnace design provided an excellent reference for evaluating the effect of the improvements made to the furnace design. In 1984, Environment Quebec conducted stack sampling for dioxin and furan emissions from the Quebec Urban Community incinerator plant. Three tests were completed, which indicated relatively high concentrations for dioxins (800 to 4000 ng/Nm^3) and furans, which is not uncommon for facilities of that vintage. The modifications made in 1986 resulted in a significant reduction in dioxin emissions as shown in Figure 5.7. By employing good operating practices, dioxin concentrations were reduced to between 40 and 100 times below the 1984 test results. Furthermore, under poor

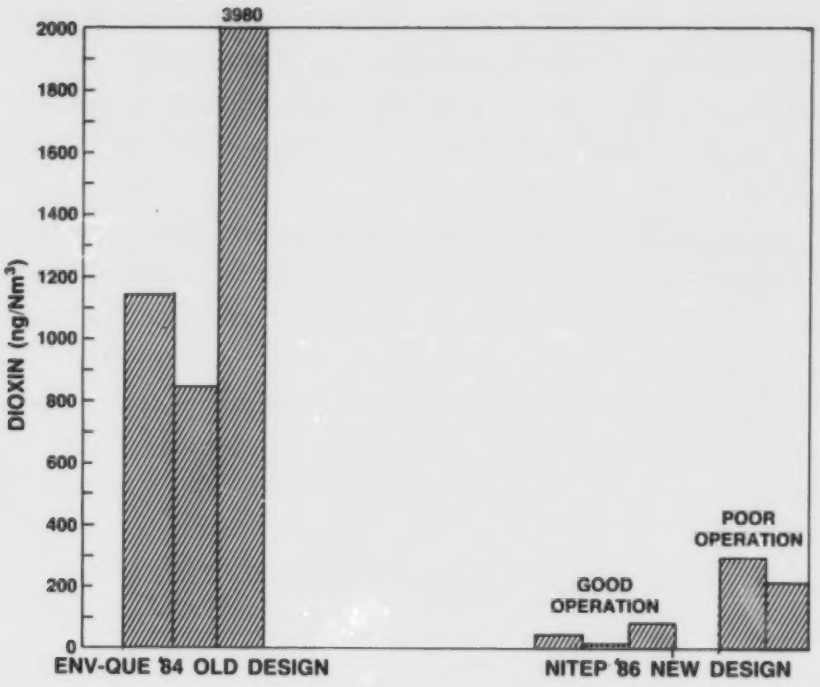


FIGURE 5.7 DIOXIN EMISSION COMPARISON

operating conditions, the reduction achieved was an order of magnitude. This indicates that, although the new design had a significant influence on dioxin emissions, good operating practice was essential in minimizing dioxin formation and emissions.

The reduction in both dioxins and particulates was approximately the same, which suggests an interrelationship. Based on current theory that dioxins are mostly bound to particulates in the combustion gases, it is postulated that good combustion conditions that reduce the carryover of particulates from the furnace will also minimize the formation and emission of dioxins into the environment. This relationship is further discussed below.

The total **dioxin** and **furan** emissions for the new design were in the range of 19 to 298 ng/Sm^3 and 44 to 306 ng/Sm^3, respectively. The lowest trace organic and carbon monoxide emissions occurred during the good operating conditions. The highest dioxin and furan concentrations corresponded to one of the two poor operating conditions, as did the highest carbon monoxide concentrations. The dioxin/furan results clearly demonstrate that incinerator operating conditions have a significant effect on emissions.

The dioxin emissions at the low and high burning rates were similar at 52.6 and 55.4 ng/Sm^3; at the design rate, with good operating conditions dioxin emissions were even lower at 18.8 ng/Sm^3. A similar trend was observed in the case of furan stack gas concentrations. Concentrations at the low and high rate operating conditions were similar (average 107.6 ng/Sm^3); the design rate concentrations were less than half at 44.5 ng/Sm^3.

Table 5.6 and Figure 5.8 summarize the homologue concentrations of dioxins and furans on a group average basis. The homologue distribution pattern for dioxins for all test conditions indicates that the lowest concentrations occurred for the tetra homologues and that concentrations increased progressively towards the octa group. On the other hand, the furan homologue pattern showed highest concentrations for the tetra or penta group, decreasing towards the octa group. These results are consistent with the other NITEP test programs.

TABLE 5.6 DIOXIN/FURAN HOMOLOGUES PER PERFORMANCE TEST MODE

	Good Conditions/ Burning Rate			Poor Conditions/ Design Burn Rate	
Homologue	Low	Design	High	Low Temp.	Poor Dist.
T4CDD	3.9	0.6*	3.8	15.8	1.5
P5CDD	5.4	1.1*	7.5	33.9	20.3
H6CDD	10.3	2.9*	19.0	77.0	51.1
H7CDD	15.2	6.1*	27.7	98.0	68.6
OCDD	17.7	8.1*	33.4	73.9	67.5
Total PCDD	52.6	18.8*	91.4	298.5	218.9
T4CDF	39.1	18.7*	42.0	89.1	103.6
P5CDF	39.9	15.0*	34.9	98.9	108.0
H6CDF	22.5	7.8*	18.5	70.6	62.2
H7CDF	12.5	2.9*	10.9	37.1	30.2
OCDF	0.5	0.1*	0.4	2.8	2.4
Total PCDF	114.5	44.5*	106.6	298.3	306.4

* Indicates the lowest value

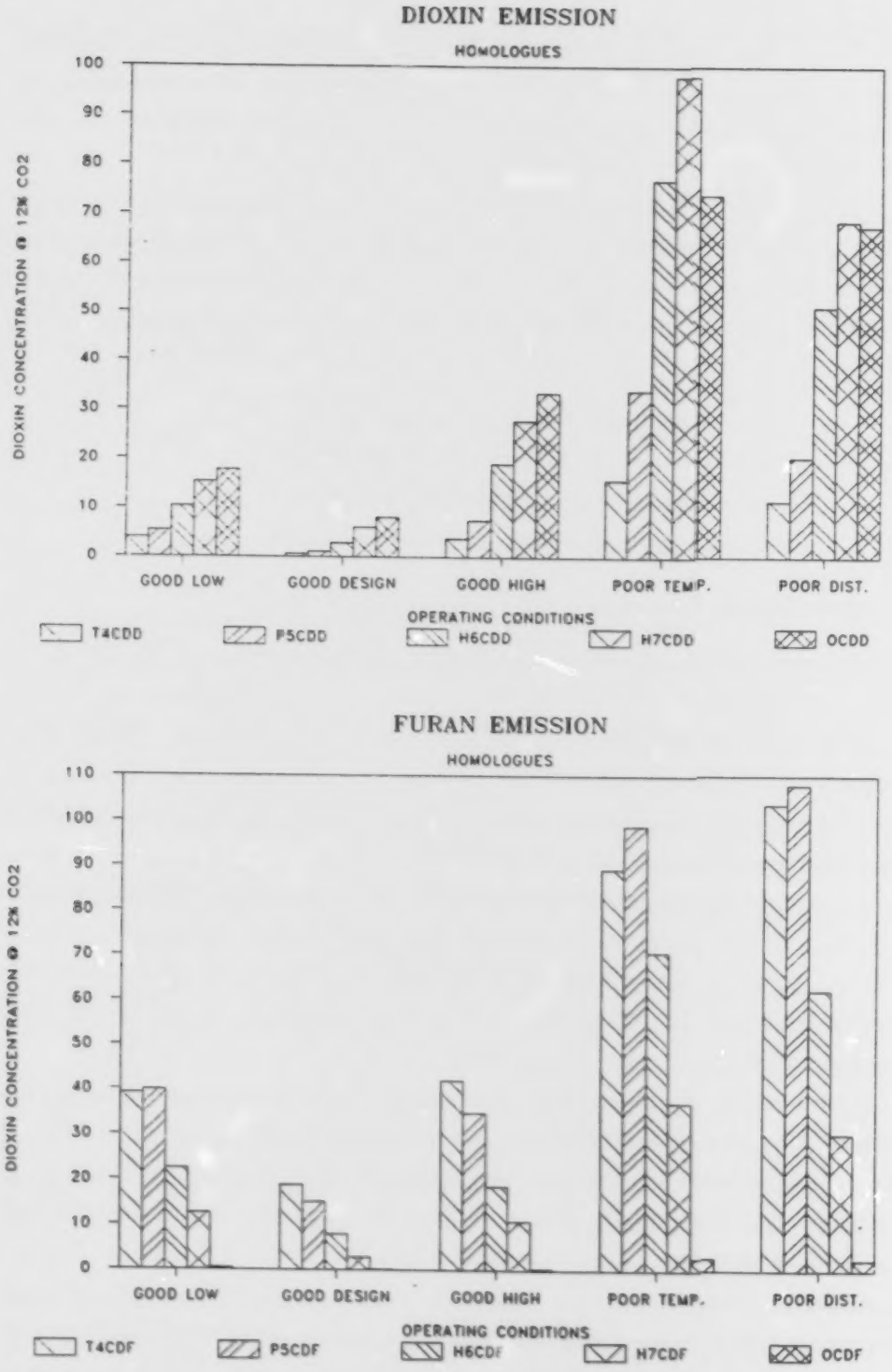


FIGURE 5.8 DIOXIN AND FURAN HOMOLOGUES

5.4.2 Other Trace Organics. As shown in Table 5.5, chlorophenol and chlorobenzene concentrations were lowest (5.1 and 3.3 $\mu g/Sm^3$, respectively) under the good operating conditions at the design rate, and highest (24 and 10 $\mu g/Sm^3$, respectively) under the poor operating conditions tests.

The polychlorinated biphenyl and polycyclic aromatic hydrocarbon emissions were lowest in the poor air distribution test group (3.2 and 1.7 $\mu g/Sm^3$, respectively) and highest in the low temperature test group (9.9 and 21.9 $\mu g/Sm^3$, respectively).

The following data summarize the range observed between group averages for these organics:

CP - The maximum was 4.6 times the minimum.
CB - The maximum was 3.0 times the minimum.
PCB - The maximum was 4.1 times the minimum.
PAH - The maximum was 6.8 times the minimum.

5.5 Particulate/Metals Emissions

Emission data for particulates and metals are summarized in Table 5.7 by group average.

All particulate concentrations were relatively low, particularly under good operating conditions. Typically, modern incinerators with highly efficient electrostatic precipitators can be expected to achieve particulate concentrations of between 20 and 70 mg/Sm^3. Considering that the incinerator tested utilized a two-stage precipitator that had been in operation for 11 years, these results were unexpectedly low. The results have been attributed to the low particulate load to the precipitator that resulted from modernization of the furnace. The lowest group average occurred for the good operating condition at the design rate, i.e., 22 mg/Sm^3. The highest concentration, 62 mg/Sm^3, occurred for the poor distribution operating condition.

The effect of the improved incinerator design on particulate emissions is well illustrated in Figure 5.9, where particulate emissions sampled by Hi-Vol trains for the old design and the new design are compared at two incinerator steam rates. Furthermore, historical particulate data from tests conducted prior to 1984 also confirm significant reductions in particulate emissions for the modified design.

As shown in Table 5.7, metal emissions (except mercury and nickel) were generally highest under the poor operating conditions and lowest under good conditions at the design rate. This also corresponds to the observation made for total particulate emissions.

TABLE 5.7 PARTICULATE/METAL EMISSIONS PER PERFORMANCE TEST MODE

	Good Conditions/ Burning Rate			Poor Conditions/ Design Burn Rate	
	Low	Design	High	Low Temp.	Poor Dist.
Particulate (mg/Sm^3)	26	22	36	55	62
Particle Size (% below 2.5 µm)	33	29	24	26	24
Cadmium ($\mu g/Sm^3$)	26	24	41	90	76
Lead ($\mu g/Sm^3$)	978	673	1599	2039	2495
Chromium ($\mu g/Sm^3$)	11	7	15	21	14
Nickel ($\mu g/Sm^3$)	9	5	8	8	7
Mercury ($\mu g/Sm^3$)	783	704	872	810	622
Antimony ($\mu g/Sm^3$)	35	36	44	112	87
Arsenic ($\mu g/Sm^3$)	2	3	5	7	6
Copper ($\mu g/Sm^3$)	39	33	54	91	89
Zinc ($\mu g/Sm^3$)	1619	1130	2061	5122	3429

Note: Values corrected to 12% carbon dioxide.

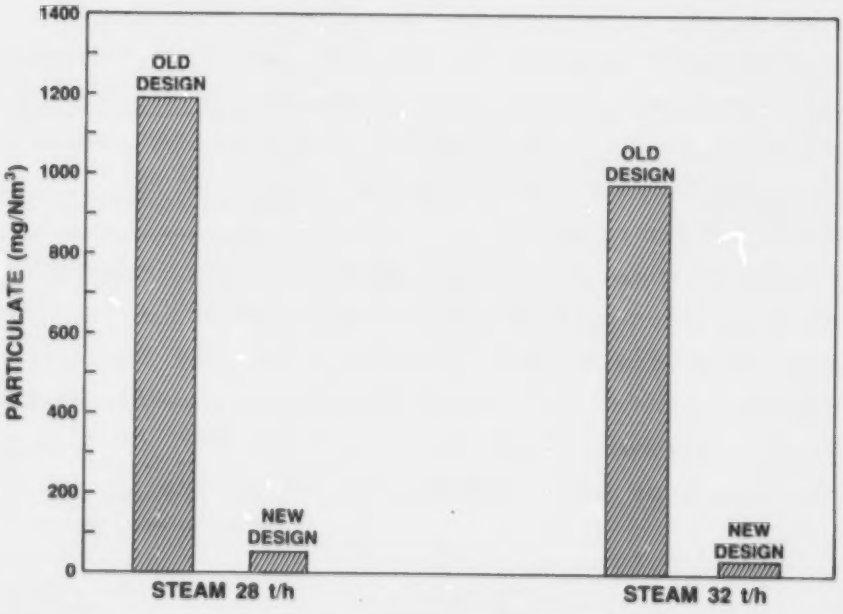


FIGURE 5.9 PARTICULATE EMISSION COMPARISON

Lead emissions appeared to correlate well with operating conditions. The highest group average was observed during the poor air distribution tests, at 3.7 times the lowest emissions, which occurred with the good operating conditions, design rate group. Similar relationships were observed for the other metals, except mercury and nickel.

Determination of the particle size distribution was carried out at the precipitator outlet at a sampling test point of average flue gas velocity. Close examination of the results did not identify any relationship between the particle size distribution and the operating mode. The results per test ranged between 11% and 40% for particles smaller than 2.5 µm, and 22% to 82% for particles smaller than 10 µm. On average, for the test program, 28% of the particles were smaller than 2.5 µm and 44% smaller than 10 µm.

5.6 Refuse Analyses

To assess variability in refuse composition and analytical reproducibility, triplicate samples were collected during PT-14. The sampling period was divided into three equal intervals, shown as groups, A, B, and C in Figure 5.10. Shredded refuse from each interval was put into a separate pile from which five samples were taken. Each sample was dried and processed and subsequently further divided into subsamples. These subsamples were analyzed separately for ultimate/proximate/higher heating value (U/P/HHV), metals, and trace organics.

The multi-sampling program revealed low variability in refuse composition within a sample, confirming good subsample homogenicity and good analytical reproducibility. These points are illustrated by the trace organics data in Table 5.8. For example, dioxin content in subsamples (Sub 1, Sub 2 and Sub 3) in sample "A" were in a similar range (17-28 ng/g). Similarly, subsamples in sample "B" (147-245 ng/g) and in sample "C" (7-11 ng/g) were in a similar range.

The multi-sampling of refuse also provided evaluation of refuse composition over time, since the three samples were taken during different periods of the test. The high variability in refuse composition between the samples indicated that refuse composition was not consistent over time. For example, dioxins in samples "A", "B" and "C" were 22, 193 and 9 ng/g, respectively. These results reaffirmed the importance of obtaining large samples for analysis as well as sampling over the complete duration of each test.

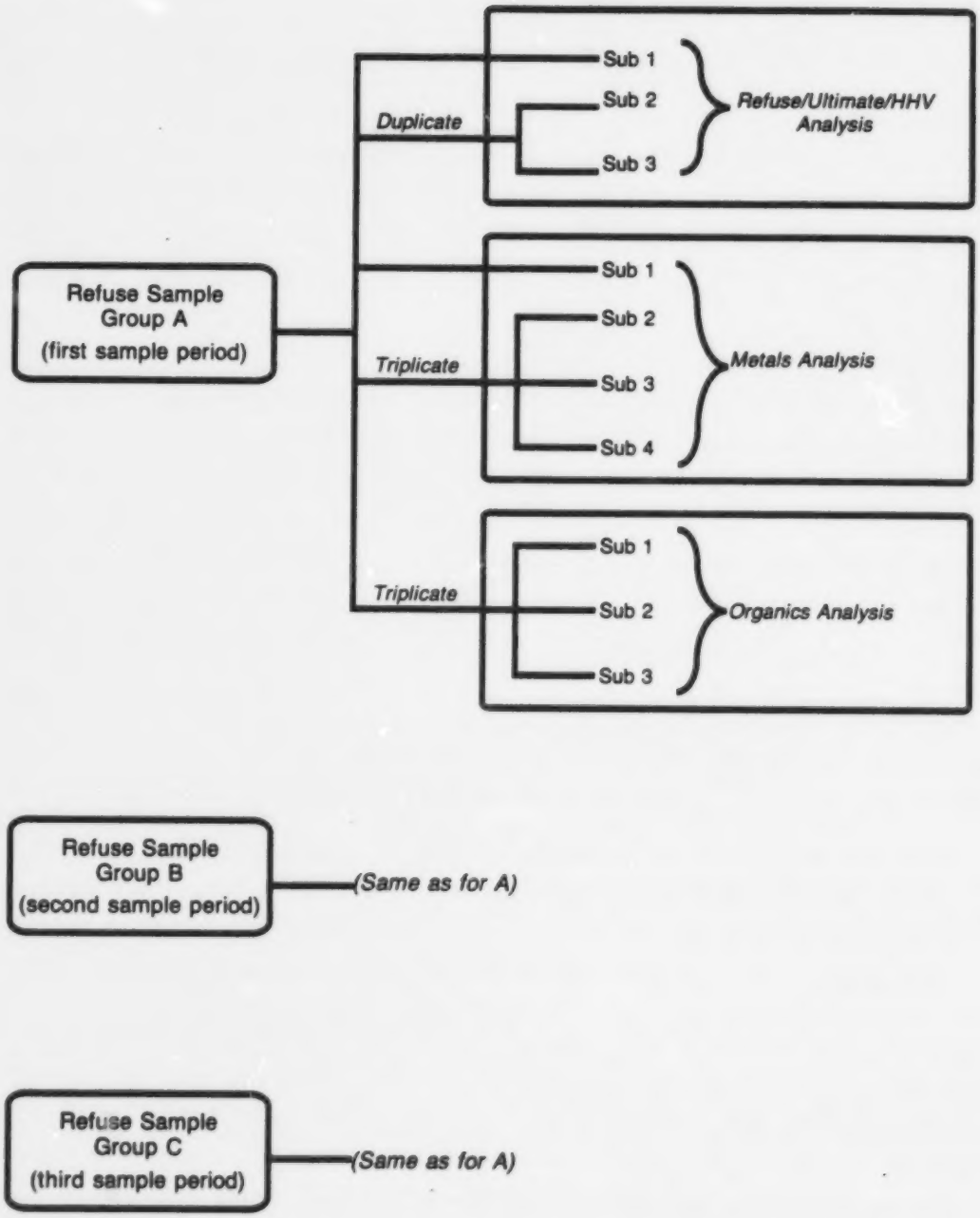


FIGURE 5.10 MULTI-SAMPLING OF REFUSE - PT-14

TABLE 5.8 TRACE ORGANICS IN REFUSE FEED SUBSAMPLES FOR TEST PT-14

	Trace Organics (ng/g)					
	PCDD	PCDF	CB	PCB	CP	PAH
Sample "A"						
SUB1	17	0.04	29	141	1097	3 942
SUB2	28	0.04	22	93	911	4 000
SUB3	21	0.04	27	45	1033	3 525
Average	22	0.04	26	93	1014	3 822
Sample "B"						
SUB1	147	9.38	87	100	5670	9 686
SUB2	245	10.71	111	84	6704	10 337
SUB3	188	9.99	96	62	4880	6 551
Average	193	10.03	98	82	5751	8 858
Sample "C"						
SUB1	7	0.04	108	26	436	2 883
SUB2	9	0.10	75	8	334	3 036
SUB3	11	0.05	92	14	538	3 227
Average	9	0.06	92	16	436	3 049
Overall Sample Average	75	3.38	72	64	2400	5 243
Standard Deviation	87	4.71	34	42	2421	2 751

Additional data on refuse composition (organics, metals, etc.) are provided in Figures 5.2 to 5.6.

5.7 Efficiency

Thermal efficiency is an appropriate indicator of good or poor operation of a combustion unit. To assess the operation of the Quebec incinerator, bomb calorimeter efficiency calculations were carried out. In the bomb calorimetric efficiency calculations, the incinerator was regarded as a bomb calorimeter to calculate the higher heating value of the refuse and subsequently the efficiency. Bomb calorimetry was chosen for efficiency calculation because this method is not affected by the refuse analysis. Secondly, most of the data used in this calculation was measured by two different means and cross-checked.

The refuse higher heating value (HHV) analyses calculated by the bomb calorimetry method ranged from 11 074 kJ/kg (4761 Btu/lb) to 13 149 kJ/kg (5653 Btu/lb). The calculated efficiencies ranged from 58% to 67%.

5.8 Radiation Chamber Temperature Stratification

Temperature measurements were taken at various locations across a horizontal plane of the furnace radiation chamber and a vertical plane at the boiler inlet. These measurements were used to develop a cross-sectional isotherm diagram showing equal temperature curves. The temperature readings for each thermocouple were averaged over the test period for each run to obtain the information plotted in Figures 5.11 and 5.12.

As seen in Figure 5.11, high temperature isotherms predominated near the rear bull-nose. The overfire air ratio between the front and rear did not appear to have any major effect on the temperature distribution; however, the isotherms seemed to indicate that the location of the main rising flame zone was near the rear bull-nose, since a low temperature zone was identified near the front wall.

Figure 5.12 indicates lower temperatures in the upper section of the boiler inlet than in the lower section. This is attributable to longer retention of the flue gas in the upper zone than in the lower zone of the boiler inlet.

5.9 Ash Analyses

Samples of incinerator (bottom) ash, boiler ash and precipitator ash were analyzed for trace organics and metals for each test and the results are discussed below.

5.9.1 Trace Organics. As shown in Table 5.9, concentrations of trace organics (except PAH) were significantly higher in precipitator ash than in boiler ash, which in turn were greater in boiler ash than in incinerator ash. Similar trends were observed in other NITEP studies (i.e., highest concentrations in the finer ash).

No significant differences in trace organic concentrations in the ashes were observed at different operating modes. However, the mass rates of boiler and precipitator ash were significantly less under good operating conditions than under poor conditions, indicating that the output rate of organics in ashes was highly dependent on operating mode.

5.9.2 Metals. Each of the three ashes were analyzed for 30 metals; Table 5.10 reports metal concentrations for the nine priority metals. For most of the metals, concentrations were highest in the precipitator ash, followed by boiler ash, and least in

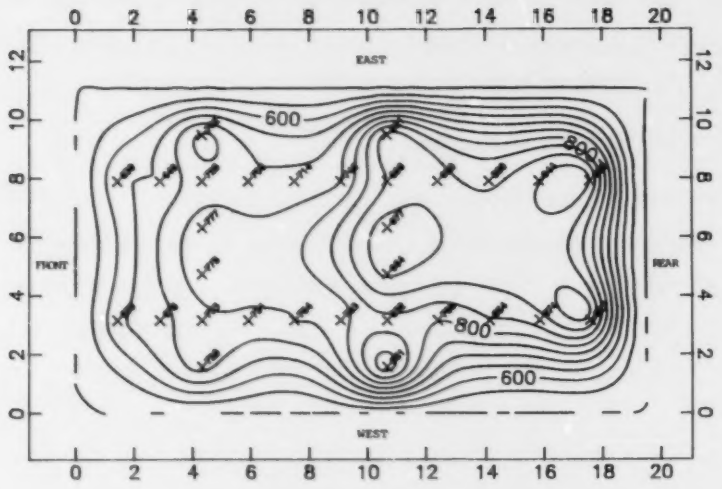


FIGURE 5.11 RADIATION CHAMBER TEMPERATURE DISTRIBUTION - CT-01

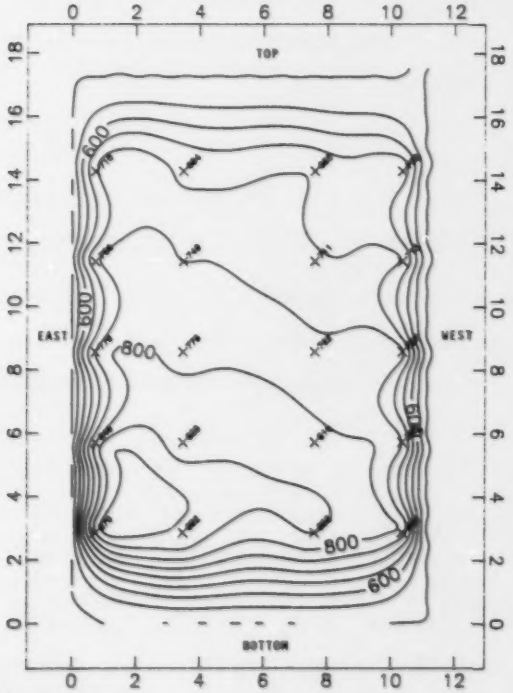


FIGURE 5.12 BOILER INLET TEMPERATURE DISTRIBUTION - CT-01

TABLE 5.9 TRACE ORGANICS IN ASHES PER PERFORMANCE TEST MODE

	Incinerator Ash (ng/g)					Boiler Ash (ng/g)					Precipitator Ash (ng/g)				
Feed Rate:	Low	Design	High	Design	Design	Low	Design	High	Design	Design	Low	Design	High	Design	Design
Temperature:	Low	Design	Design	Low	Low	Low	Design	Design	Low	Low	Low	Design	Design	Low	Low
Conditions:	Good	Good	Good	Poor	Poor	Good	Good	Good	Poor	Poor	Good	Good	Good	Poor	Poor
PTs	2-10-11	5-6-12	7-9	3-4	14-15	2-10-11	5-6-12	7-9	3-4	14-15	2-10-11	5-6-12	7-9	3-4	14-15
PCDD	0.11	0.21	-	0.16	-	135	37	23	43	51	757	584	620	605	945
PCDF	0.12	1.01	-	-	-	122	31	26	25	17	219	186	257	233	260
CB	16	45	4	5	4	1567	356	531	311	259	963	892	1663	1381	1515
PCB	-	-	-	-	-	-	-	-	-	-	5	-	-	12	24
CP	10	16	20	-	11	112	80	102	68	59	1242	1820	1701	1287	2968
PAH	153	538	498	155	320	71	25	21	33	69	101	111	103	122	331

"-" = non-detectable

TABLE 5.10 METALS IN ASHES PER PERFORMANCE TEST MODE

	Incinerator Ash (ng/g)					Boiler Ash (ng/g)					Precipitator Ash (ng/g)				
Feed Rate:	Low	Design	High	Design	Design	Low	Design	High	Design	Design	Low	Design	High	Design	Design
Temperature:	Low	Design	Design	Low	Low	Low	Design	Design	Low	Low	Low	Design	Design	Low	Low
Conditions:	Good	Good	Good	Poor	Poor	Good	Good	Good	Poor	Poor	Good	Good	Good	Poor	Poor
PTs	2-10-11	5-6-12	7-9	3-4	14-15	2-10-11	5-6-12	7-9	3-4	14-15	2-10-11	5-6-12	7-9	3-4	14-15
Antimony	12	16	9	26	10	342	332	270	96	245	553	753	525	730	328
Arsenic	7.7	6.8	8.3	5.7	7.7	83	91	74	45	54	133	170	130	67	46
Cadmium	3.4	3.8	2.8	3.6	4.2	286	206	153	135	211	877	1062	764	514	475
Chromium	230	250	363	231	171	331	304	338	318	235	454	479	516	527	348
Copper	1773	2543	4509	2245	1308	636	530	480	541	528	1323	1483	1295	946	926
Lead	766	1757	867	1323	1638	9323	7478	6635	5511	8655	20667	21133	17150	10750	11800
Mercury	0.0027	0.0311	0.0418	0.0087	0.0038	8.3	6.8	5.9	3.6	2.9	49	72	73	32	41
Nickel	102	131	428	89	72	111	115	101	113	109	100	108	118	98	108
Zinc	2307	1783	1531	2551	1172	17600	17400	15650	11100	12750	60900	60700	44750	33800	27300

the incinerator ash, following the pattern observed for trace organics. However, copper concentrations were highest in incinerator ash, followed by precipitator ash. Nickel concentrations were similar in all three ashes.

As for trace organics, no significant differences in metal concentrations in the ashes were observed for the different operating modes. However, the mass rates of boiler and precipitator ash were significantly less under good conditions, indicating that the overall output of metals in fly ashes is highest under poor operating conditions.

5.10 Plastics Classification

To determine the amount and types of plastics found in the incoming refuse, a plastic classification program was performed during the performance tests. Since each classification procedure took approximately two days to perform, only eight assessments were carried out.

The program results indicated that plastic in the refuse varied from 5.6% to 10.1%, with an average of 7.9%. The total plastic was 54% plastic films (mainly garbage bags), 42% rigid or molded plastics, and 4.6% foam by weight.

The polyolefins, polyethylene and polypropylene represented the largest category of plastics in the refuse, 63.0% of the total weight. These compounds are most widely used in garbage bags and packaging because of their low cost and valuable properties.

Polystyrene was the second largest category, with 27.2% of the total plastic composition. It was estimated that in Quebec, 80% of the polystyrene is found in rigid containers.

The smallest plastics component was polyvinyl chloride (PVC) with only 6.3% of the total plastic composition. Polyvinyl chloride is used mostly in transparent rigid containers but, due to its high cost, it is not widely used.

5.11 Input/Output of Metals and Organics

5.11.1 Metals. A mass balance was completed to determine the distribution of metals throughout the incineration process. The metals on the priority list were examined in the mass balance. The input of each metal in the refuse feed was compared against the output of each metal in all output streams (i.e., precipitator ash, boiler ash, incinerator ash and stack emissions). The data was normalized "per tonne of refuse" for each test. Table 5.11 provides an input/output summary for seven of the priority metals. In general, the calculated metal output was higher than the calculated metal input by approximately

TABLE 5.11 METALS INPUT/OUTPUT

Metal	Input (g/t refuse)	Output (g/t refuse)	Out/In Ratio
Cr	102	70	0.7
Pb	314	580	1.9
Ni	23	44	1.9
Sb	3	10	3.4
As	1	3	3.2
Cd	5	8	1.8
Zn	218	981	4.5

a factor of two. In Table 5.11, only chromium showed a lower output than input. In view of the difficulty in obtaining representative bottom ash and refuse samples, the mass balance for metals was considered acceptable. Similar test programs elsewhere have shown a similar closure on metals mass balances (6).

5.11.2 Trace Organics. Since trace organics can be both created as well as destroyed during various steps of the incineration process, no mass balance is possible for these compounds. However, an input/output comparison for compounds such as dioxins and furans provides an interesting indication of net decrease or net increase of these compounds.

As shown in Figure 5.13, there was a substantial net decrease in dioxins (expressed per tonne of refuse), as indicated by the output/input ratio of 0.3. For furans, the output/input ratio was about 2, showing a net increase. Similar results were obtained during the NITEP P.E.I. tests.

Figure 5.14 indicates a significant net decrease for polychlorinated biphenyls and chlorophenols, and a very slight increase for chlorobenzenes.

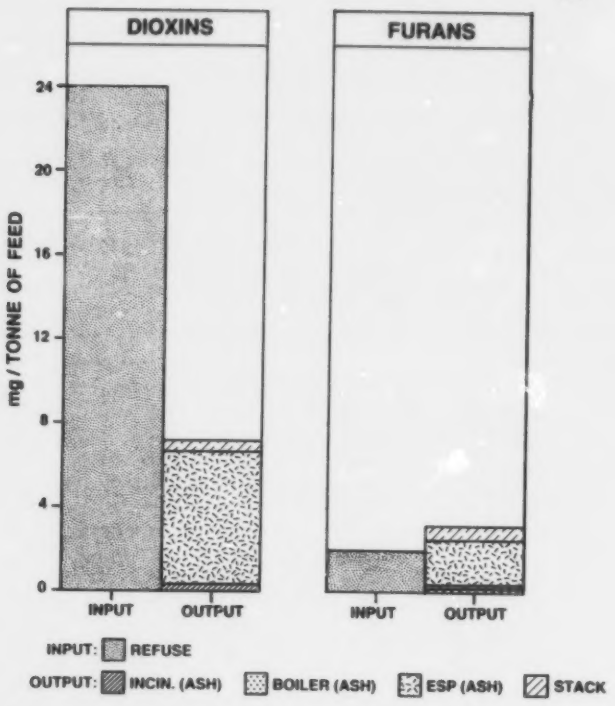


FIGURE 5.13 INPUT/OUTPUT FOR DIOXINS AND FURANS (all tests averaged)

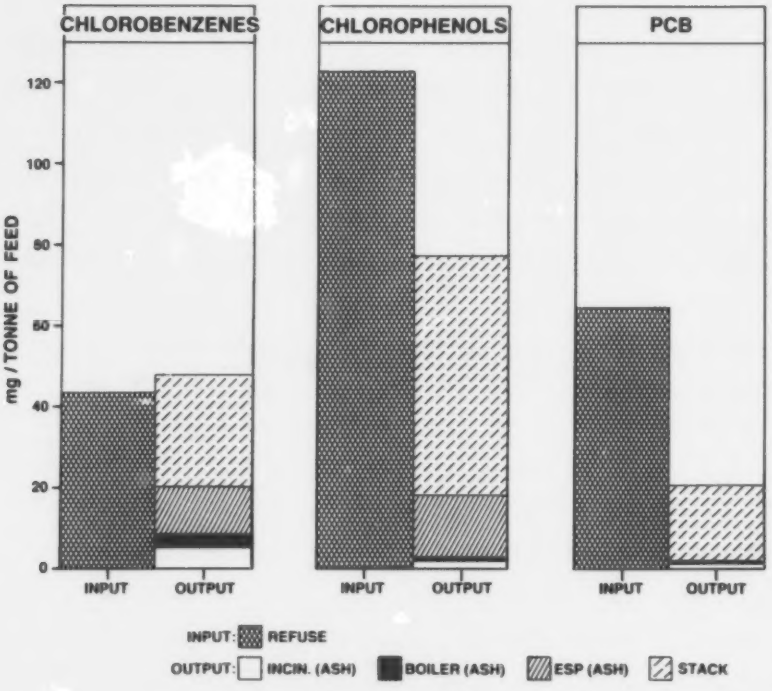


FIGURE 5.14 INPUT/OUTPUT FOR CHLOROBENZENES, CHLOROPHENOLS, AND POLYCHLORINATED BIPHENYLS (all tests averaged)

6 PROCESS AND EMISSION CORRELATIONS

This chapter summarizes the statistical analyses carried out on 148 parameters using individual test data. All parameters were analyzed using correlations to determine the most significant findings. These correlations were subjected to several levels of screening which determined their significance for further discussion.

The statistical analyses consisted of the following correlations and objectives:

- simple linear regression of selected organic and inorganic emissions versus continuous emission data and process operating variables, to identify the most important parameters for multiple linear regression; and
- multiple linear regression of selected organic emissions versus continuous emission data and process operating variables, to develop a model which could be employed in predicting and/or controlling organic emissions.

6.1 Statistical Analysis Methodology

The statistical analysis technique used to identify correlation relationships was regression analysis. This technique generates a mathematical model that best describes the relationship between sets of data. Regression models are used for describing data, estimating unknown values, and most importantly in this study, for predicting and estimating emissions from other variables.

To determine a relationship between pairs of variables, regression analysis is used to "fit" a function to the data. In most research it is difficult to find a regression line, especially a straight one, that perfectly fits the data. A measure of the "goodness of fit" is given by "r", the correlation coefficient, and "r^2, the determination coefficient.

The sign of "r" can be positive or negative. A positive sign indicates that both sets of variables increase or decrease together. A negative sign indicates that one will increase when the other decreases. When there is a perfect fit (no error), the value of r is $\pm$ 1.0 and the sign depends upon the slope of the line. Similarly a value of 0 denotes total absence of a linear relationship.

The determination coefficient, "r^2", is the square of the correlation coefficent "r". It is optimized in statistics because it eliminates the negative sign which "r" may have, thus providing a convenient way of comparing the "goodness of fit" of different regression models. Furthermore, r^2 describes the portion of the total variance that is

explained by the correlation. Hence, the closer the r^2 value is to 1.0, the better the "goodness of fit".

The r^2 value essentially is a measure of total variance explained by a linear correlation between two variables. Values of r^2 can be judged on a relative basis (comparing parameter to parameter) or on an absolute basis (defining a minimum value of r^2 for a correlation to be judged acceptable). Colton (7) suggests that values of r^2 for different levels of fit can range from 0.13 to 0.56. Larger values of r^2 than those suggested by Colton to describe the same range of relationships (poor, good, excellent) are probably appropriate for this study and have been suggested by NRC (8). Table 6.1 provides the information for experimental correlation data. Each of these references assumes that a sufficiently large number of data points are used to provide the r^2 values. Large sample sizes effectively lower the level at which a correlation between two variables becomes significant.

TABLE 6.1 SIGNIFICANCE OF EXPERIMENTAL CORRELATION DATA

Correlation	r^2 Colton (7)	r^2 Controlled Experiment	r^2 Field Study
Little or No	0.13		
Fair	0.25	0.50	0.45
Moderate	0.56	0.65	0.55
Good	>0.56	0.80	0.65
Very Good	-	0.90	0.80
Excellent	-	0.95	0.90

For this test program, 13 pairs of data were selected for simple linear regression analysis based on 13 test runs. From a standard statistical correlation table, the critical r^2 value for 13 pairs of data for a 5% significance is 0.306. The use of the critical value at the 5% significance level allows one to determine if correlations exist between variables. Therefore, for 13 pairs of data (5% significance), if the calculated r^2 value is less than 0.306, no correlation exists between the compared variables. Once it is established that a correlation exists for any r^2 value, the relative strength of the fit between different parameters can be assessed from the data in Table 6.1.

For the simple and multiple linear regression models, the calculation of the r^2 value was based upon standard statistical practice involving the calculation of both the standard deviations of the various data sets and the co-variance between the data sets.

6.2 Data Analysis Strategy

6.2.1 Dependent Variables. One of the primary objectives of this study was to assess the influence of different operating conditions on emissions. These emissions were designated the dependent variables for the purposes of the data analysis. The emissions (dependent variables) of particular interest were:

- dioxins (PCDD),
- furans (PCDF),
- chlorophenols (CP),
- chlorobenzenes (CB),
- polycyclic aromatic hydrocarbons (PAH),
- polychlorinated biphenyls (PCB),
- particulates, and
- heavy metals.

7.2.2 Independent Variables. The independent variables employed in the data analysis were selected keeping the following two objectives in mind, namely:

1) Prediction Models - to establish a method of predicting the amounts of the above pollutants from more readily measurable parameters (surrogates), and
2) Control Models - to identify operating conditions or limits that when adhered to, would control and minimize the concentrations of pollutants leaving the incinerator.

To attain these objectives, the independent variables were separated into two groups. Those that were used to generate the prediction models are referred to as the "monitoring variables". Those that were used to generate the control models are referred to as the "operating variables".

The prediction model monitoring variables were:

i) lower radiation chamber temperature (°C),
ii) upper radiation chamber temperature (°C),
iii) excess air expressed by excess oxygen (%),
iv) flue gas moisture (%),
v) carbon monoxide concentration in the flue gas (ppm), and

vi) nitrogen oxides concentration in the flue gas (ppm).

The control model operating variables were:

i) primary air (i.e., underfire air) (Sm^3/min),
ii) secondary air (i.e., overfire air) (Sm^3/min),
iii) total air (Sm^3/min),
iv) primary/secondary air ratio,
v) secondary front/rear ratio, and
vi) throughput expressed as steam rate (t/h).

6.3 Correlations and Simple Linear Regression Analysis

6.3.1 Dioxins. Dioxin is viewed by the scientific community as an important trace organic compound that can be controlled in the combustion process of a municipal waste incinerator. As will be shown, significant relationships were found between dioxin concentration and a number of monitoring and operating variables.

For the purpose of this study, it was assumed that the effectiveness of the electrostatic precipitator to remove trace organics was constant. This assumption was based on the relatively constant efficiency of the precipitator in removing particulates and metals, and on the good correlation between particulate and dioxin emissions (r^2 = 0.64).

Table 6.2 presents the correlations between dioxin concentration and the selected operating variables. The correlation of primary air flow with dioxins was significant, with an r^2 value of 0.83. It is interesting to note that when the incinerator was operating under "good" conditions, dioxin emissions showed no correlation with the primary air flow rate. On the other hand, a strong correlation was obtained when all operating conditions were considered, as shown in Figure 6.1.

As shown, in Table 6.3, weak correlations were obtained for dioxin emissions and lower radiation chamber, upper radiation chamber and boiler inlet temperatures. However, closer examination of the scatter plot in Figure 6.2 indicates a significant correlation between PCDD emissions and incinerator temperature, if test points 2, 10 and 11 (low feed rate) are considered to be part of a second family of curves. The remaining tests (which are at the design and high feed rates) provide correlations with significant r^2 values of over 0.7. Unfortunately, there were only three tests at the low rate; data for other temperatures at this rate are needed to conclusively determine if two separate curves do exist.

TABLE 6.2 DIOXIN CORRELATIONS WITH OPERATING VARIABLES

Correlated Parameters	Determination Coefficients (r^2)
Primary Air (Sm^3/min)	0.83 (Very Good correlation)
Secondary Air (Sm^3/min)	0.04 (No)
Total Air (Sm^3/min)	0.51 (Fair)
Primary/Secondary Air Ratio	0.14 (No)
Secondary Front/Rear Ratio	0.01 (No)
Steam Rate (t/h)	0.08 (No)

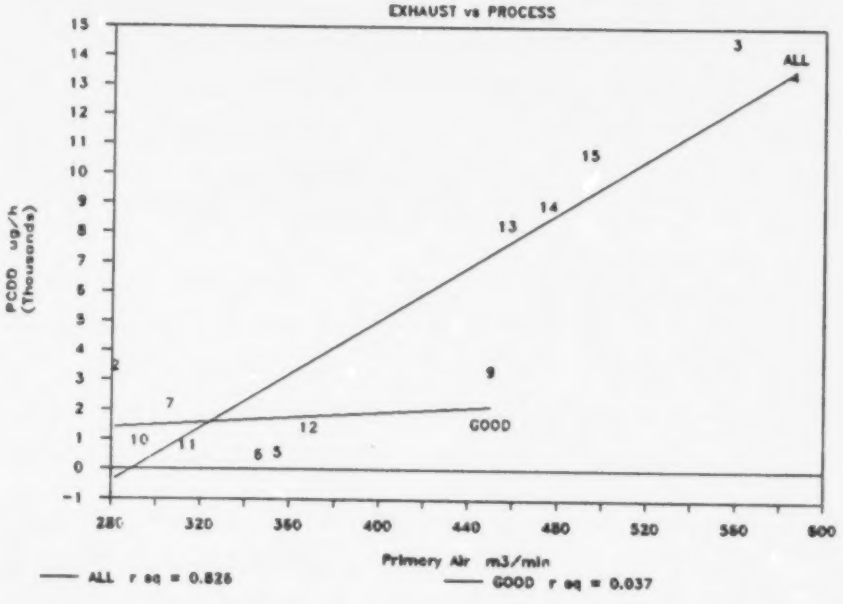


FIGURE 6.1 CORRELATION BETWEEN DIOXINS AND PRIMARY AIR FLOW

A comparison of carbon monoxide and total dioxin concentration indicated a fair correlation ($r^2 = 0.50$) as shown in Figure 6.3. However, no correlation occurred when only good operating conditions were considered (i.e., below 50 ppm CO).

Determination coefficients in Table 6.3 for dioxin versus nitrogen oxides, hydrogen chloride, sulphur dioxide, and excess air ranged from very good to no

TABLE 6.3 DIOXIN CORRELATIONS WITH MONITORING VARIABLES

Correlated Parameters	Determination Coefficients (r^2)
Lower Radiation Chamber Temp. (°C)	0.15 (No correlation)
Upper Radiation Chamber Temp. (°C)	0.20 (No)
Excess Air	0.16 (No)
Flue Gas Moisture (%)	0.05 (No)
Carbon Monoxide	0.50 (Fair)
Nitrogen Oxides	0.38 (Poor)
Sulphur Dioxide	0.31 (Poor)
Hydrogen Chloride	0.12 (No)
Particulate	0.64 (Good)
Cadmium	0.74 (Very good)
Copper	0.77 (Very good)
Zinc	0.70 (Very good)
Boiler Inlet Temp. (°C)	0.15 (No)

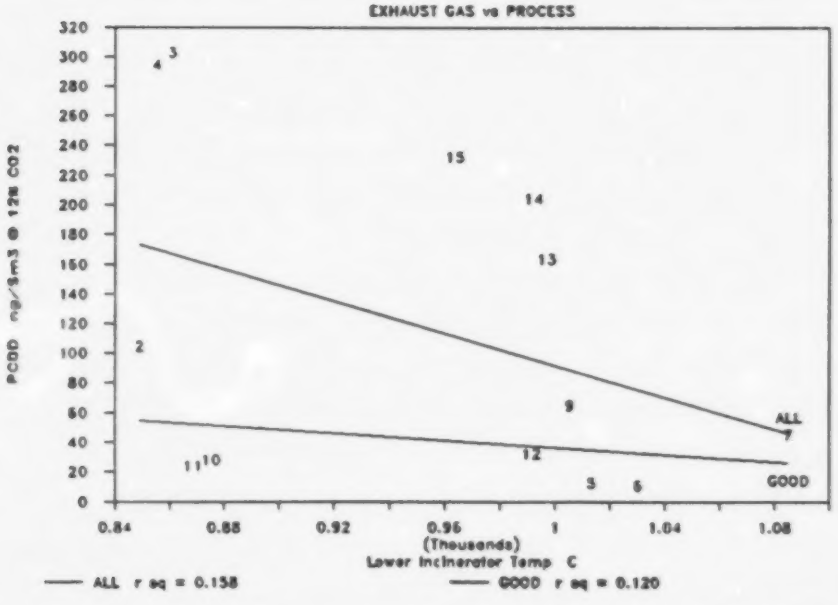


FIGURE 6.2 CORRELATION BETWEEN DIOXINS AND LOWER RADIATION CHAMBER TEMPERATURE

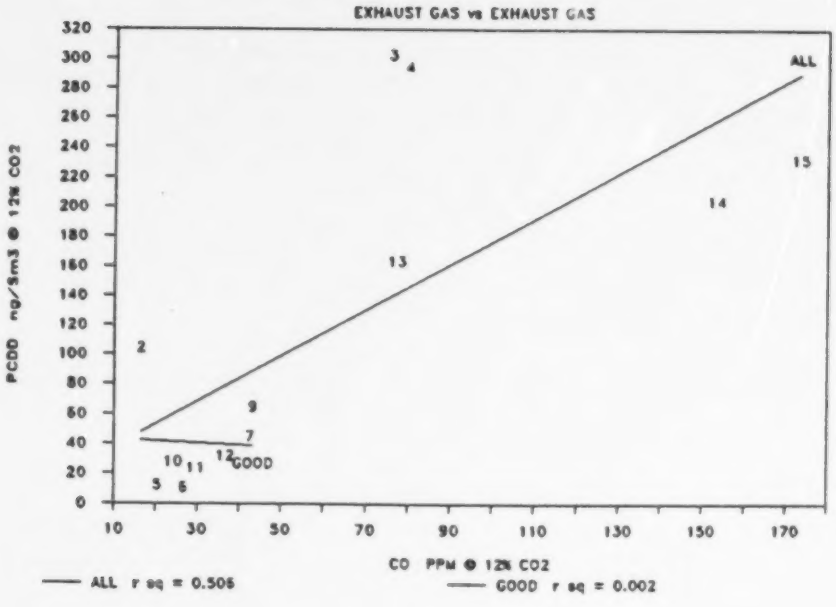


FIGURE 6.3 CORRELATION BETWEEN DIOXINS AND CARBON MONOXIDE

correlation. Correlations of dioxins with emissions of particulates and select metals (cadmium, copper and zinc) were very strong. Of particular importance is the strong correlation between the dioxin and copper concentrations. It has been suggested by other studies that copper may be a catalyst for the formation of dioxin. This appears to be supported by the very good resultant correlation coefficient of $r^2 = 0.77$ (9,10).

6.3.2 Furans. As previously shown for dioxins, significant relationships were found for furans versus monitoring, operating and other variables.

The furan correlations in the exhaust gas in comparison with the selected operating variables are shown in Table 6.4. As was the case for dioxins, furan concentrations showed strong correlations with exhaust gas flow and primary air (as shown in Figure 6.4) with r^2 values of 0.76 and 0.68, respectively. Unlike the dioxins, furans showed no correlation with secondary air.

As shown in Figure 6.5 and Table 6.5, no significant correlations appeared to exist between furans and process temperatures. However, a closer examination of the scatter plot indicates that similar conclusions may be drawn as for dioxins, i.e., the possibility of a second family of curves.

TABLE 6.4 FURAN CORRELATIONS WITH OPERATING VARIABLES

Correlated Parameters	Determination Coefficients (r^2)
Primary Air (Sm^3/min)	0.68 (Good correlation)
Secondary Air (Sm^3/min)	0.00 (No)
Total Air (Sm^3/min)	0.29 (Fair)
Primary/Secondary Air Ratio	0.26 (Fair)
Secondary Front/Rear Ratio	0.09 (No)
Steam Rate (t/h)	0.05 (No)

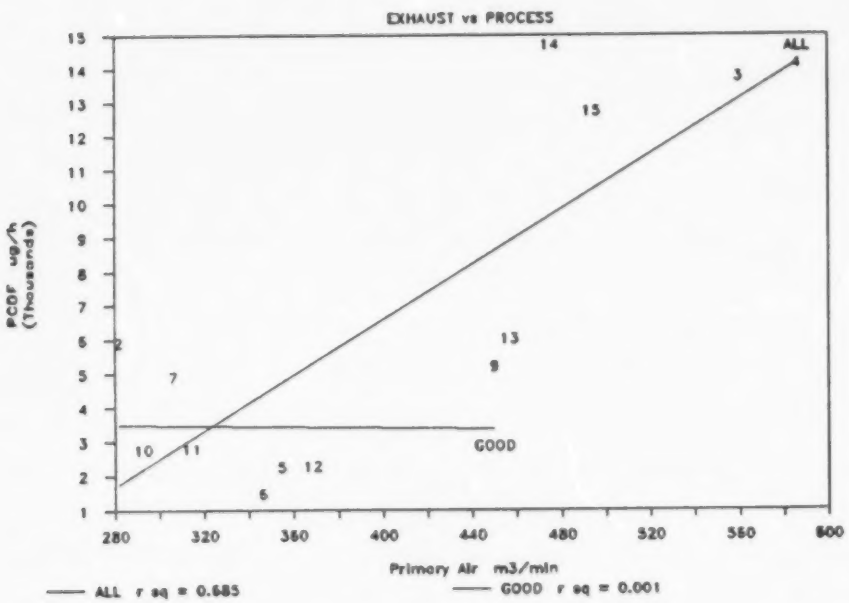


FIGURE 6.4 CORRELATION BETWEEN FURANS AND PRIMARY AIR FLOW

As anticipated, furan concentration showed a strong correlation with carbon monoxide concentrations, with an r^2 value of 0.61. However, furan concentrations showed weak correlations with emissions of nitrogen oxides, hydrogen chloride, sulphur dioxide, and excess air.

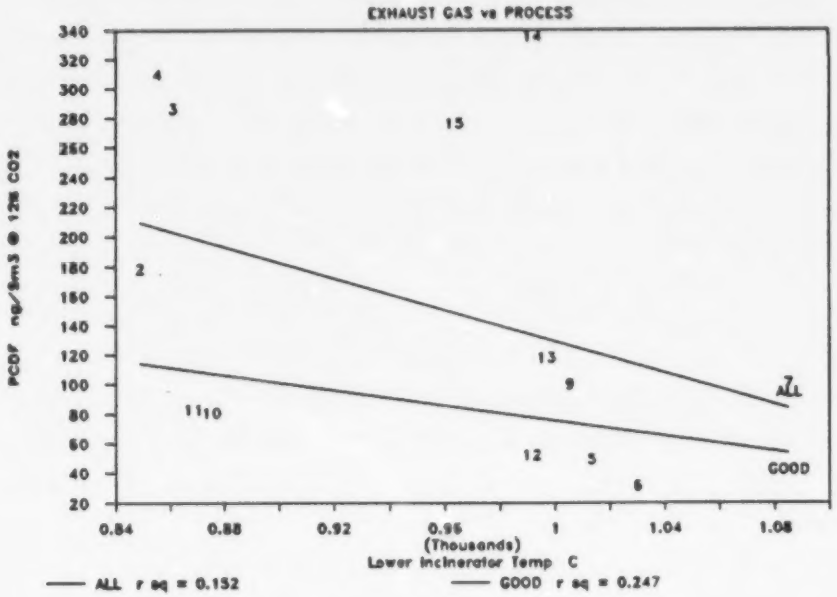


FIGURE 6.5 CORRELATION BETWEEN FURANS AND LOWER RADIATION CHAMBER TEMPERATURE

TABLE 6.5 FURAN CORRELATIONS WITH MONITORING VARIABLES

Correlated Parameters	Determination Coefficients (r^2)
Lower Radiation Chamber Temp. (°C)	0.15 (No correlation)
Upper Radiation Chamber Temp. (°C)	0.25 (No)
Excess Air	0.24 (No)
Flue Gas Moisture (%)	0.15 (No)
Carbon Monoxide	0.60 (Good)
Nitrogen Oxides	0.28 (Poor)
Sulphur Dioxide	0.32 (Poor)
Hydrogen Chloride	0.14 (No)
Particulate	0.63 (Good)
Cadmium	0.75 (Very good)
Copper	0.72 (Very good)
Zinc	0.63 (Very good)
Boiler Inlet Temp. (°C)	0.18 (No)

In the previous section, it was suggested that copper may act as a catalyst in the formation of some trace organics. Trace metal concentrations in the exhaust gases were compared to furan emissions, as shown in Table 6.5. Copper (r^2 = 0.72) and cadmium (r^2 = 0.70) showed strong correlations and to a slightly lesser degree so did particulate (r^2 = 0.63) and zinc (r^2 = 0.63). No correlations appeared to occur with either polycyclic aromatic hydrocarbon or polychlorinated biphenyl concentrations when all the test runs were considered.

6.3.3 Particulates. The particulate concentration in the exhaust gas was compared to a wide variety of parameters to determine whether correlations existed. Primary air and flue gas flows, with r^2 = 0.62 and r^2 = 0.69, respectively, showed strong correlations. As previously discussed, combustion air flows through the grates have a direct impact on the solids carrying potential of the incineration system. Accordingly, particulate concentrations are expected to vary directly with air flow.

Correlations between particulates and organic emissions in exhaust gases were good. As previously discussed, strong correlations were found with dioxins (r^2 = 0.64) and furans (r^2 = 0.62). In addition, the correlation of chlorobenzenes with particulates was also quite good (r^2 = 0.67), but was lower with chlorophenols (r^2 = 0.46).

As anticipated, significant correlations were found between particulate emission concentrations and selected trace metal concentrations, such as cadmium, copper, and lead, with r^2 values of 0.86, 0.94 and 0.90, respectively.

6.3.4 Metals. As previously discussed, it has been suggested that heavy metals may act as catalysts in the formation of dioxins, furans, chlorobenzenes and chlorophenols. Possible catalyst candidates include antimony, cadmium, chromium, copper and zinc. From the data presented in Table 6.6, a number of strong correlations support this theory. For example, dioxins and furans correlate well with six of the nine metals listed. To a slightly lesser degree, chlorobenzenes and chlorophenols also correlated with these same metals. However, correlations were poor when mercury and nickel were compared to all organic data (i.e. r^2's of approximately 0.1).

No correlations were found for the polycyclic aromatic hydrocarbons and polychlorinated biphenyls when compared to any of the metals.

Correlations for priority metals in the refuse with emissions of metals on a rate basis were all very weak, with the exception of antimony (r^2 = 0.53). This suggests some problems in the sampling procedures employed. During testing, some oversized pieces of metal were removed prior to shredding and analysis. Improved methods for

TABLE 6.6 DETERMINATION COEFFICIENTS (r^2) FOR METAL EMISSIONS VERSUS TRACE ORGANICS

Organic Emission	Sb	As	Cd	Cr	Cu	Pb	Hg	Ni	Zn
PCDD	0.77	0.35	0.74	0.59	0.77	0.48	0.01	0.11	0.70
PCDF	0.54	0.43	0.70	0.44	0.72	0.52	0.00	0.05	0.63
CB	0.65	0.38	0.77	0.55	0.34	0.58	0.03	0.11	0.64
CP	0.50	0.31	0.51	0.41	0.61	0.40	0.00	0.07	0.45
PAH	0.06	0.03	0.13	0.14	0.08	0.00	0.10	0.01	0.13
PCB	0.00	0.00	0.01	0.08	0.00	0.00	0.09	0.09	0.00

obtaining representative refuse samples will be required for future test programs to improve the accuracy that can be attained in metals mass balances.

6.3.5 Carbon Monoxide. Figure 6.6 shows the correlation of a number of trace organic emissions in the exhaust gas with carbon monoxide. In addition to the relatively strong correlations found between dioxins and carbon monoxide, and furans and carbon monoxide, similar correlations were found between chlorobenzenes and chlorophenols, and carbon monoxide. It has been suggested that a relationship may exist between trace organics emissions and carbon monoxide levels. For dioxins and furans, these results to some degree tend to corroborate this theory. Other important organics, such as polycyclic aromatic hydrocarbons (r^2 = 0.0) and polychlorinated biphenyls (r^2 = 0.05), showed no correlation. No correlations occurred between carbon monoxide and trace organics when only "good" operating condition test results were considered. This can be attributed to the assumption that under the good operating conditions (i.e., below 50 ppm), the data tended to cluster, making correlations difficult.

6.4 Multiple Linear Regression Analysis - Organics Emissions

6.4.1 General. The second phase of data analysis employed multiple linear regression analysis. The coefficients of determination obtained from the multiple regression models for trace organic emissions are summarized in Table 6.7. These results show that significantly better fits were achieved with multiple over simple regression analysis. The multiple regression models resulted in r^2 values of 0.8 to 0.9 for dioxins, furans, chlorophenols and chlorobenzenes compared to the range of 0.5 to 0.8 using simple

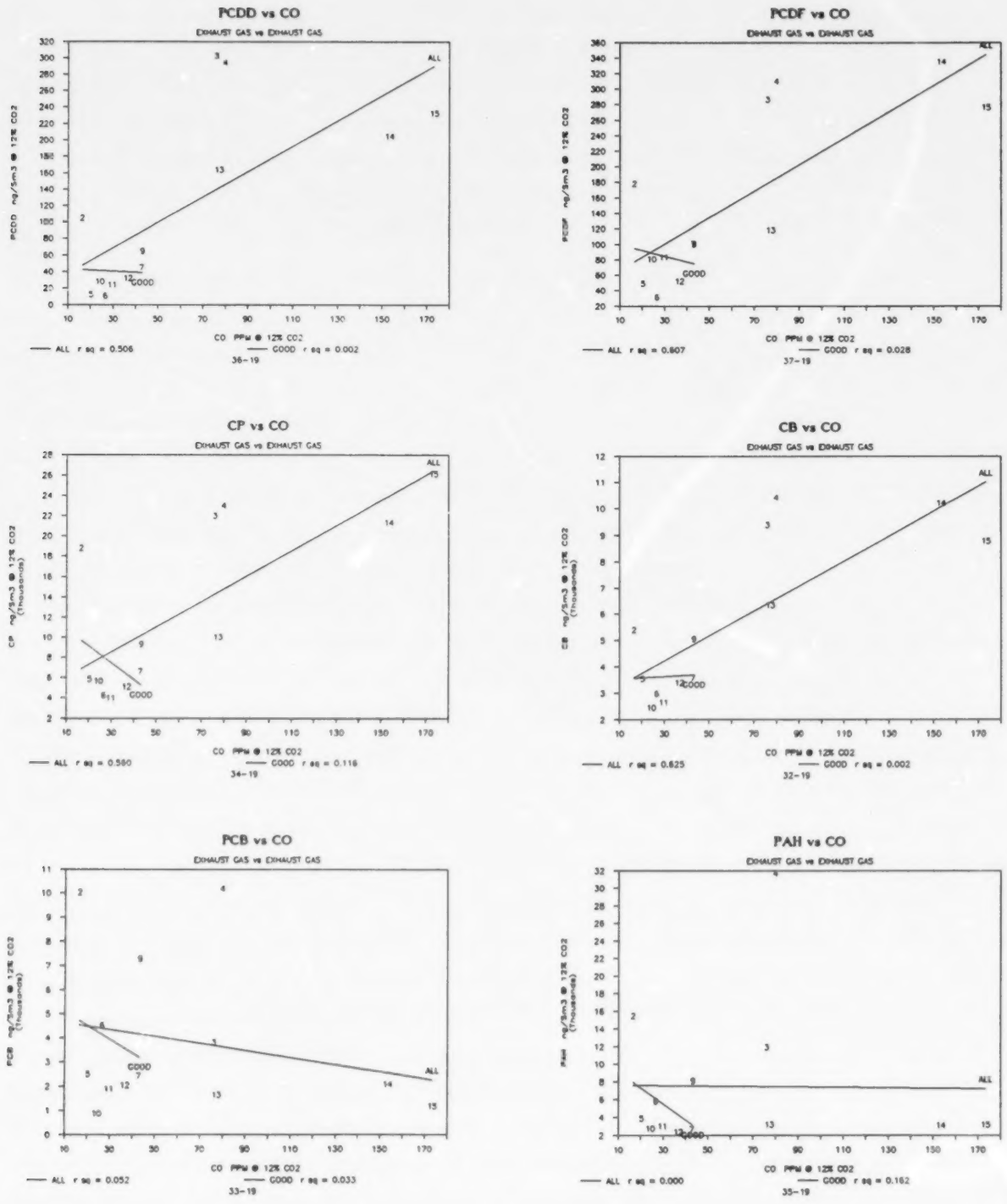

PCDD vs CO
EXHAUST GAS vs EXHAUST GAS
PCDD ng/Sm3 @ 12% CO2
CO PPM @ 12% CO2
ALL r sq = 0.506
GOOD r sq = 0.002
36-19
PCDF vs CO
EXHAUST GAS vs EXHAUST GAS
PCDF ng/Sm3 @ 12% CO2
CO PPM @ 12% CO2
ALL r sq = 0.807
GOOD r sq = 0.028
37-19
CP vs CO
EXHAUST GAS vs EXHAUST GAS
CP ng/Sm3 @ 12% CO2 (Thousands)
CO PPM @ 12% CO2
ALL r sq = 0.580
GOOD r sq = 0.116
34-19
CB vs CO
EXHAUST GAS vs EXHAUST GAS
CB ng/Sm3 @ 12% CO2 (Thousands)
CO PPM @ 12% CO2
ALL r sq = 0.625
GOOD r sq = 0.002
32-19
PCB vs CO
EXHAUST GAS vs EXHAUST GAS
PCB ng/Sm3 @ 12% CO2 (Thousands)
CO PPM @ 12% CO2
ALL r sq = 0.052
GOOD r sq = 0.033
33-19
PAH vs CO
EXHAUST GAS vs EXHAUST GAS
PAH ng/Sm3 @ 12% CO2 (Thousands)
CO PPM @ 12% CO2
ALL r sq = 0.000
GOOD r sq = 0.162
35-19

FIGURE 6.6 CARBON MONOXIDE CORRELATIONS

TABLE 6.7 SUMMARY OF DETERMINATION COEFFICIENTS FOR REGRESSION MODELS

Organic Emission	Simple Regression		Multiple Regression	
	Prediction Models (r^2)	Control Models (r^2)	Prediction Models (r^2)	Control Models (r^2)
Dioxin	0.51	0.77	0.89	0.89
Furan	0.61	0.55	0.90	0.84
CP	0.56	0.50	0.86	0.77
CB	0.62	0.67	0.87	0.82
PAH	0.67	0.40	0.73	0.63
PCB	0.54	0.16	0.62	0.27

regression. This suggests that the multiple regression models would be better tools in identifying the independent variables that can be used to predict and to control emissions of dioxins, furans, chlorophenols and chlorobenzenes.

As was stated at the beginning of the chapter, the selection of independent variables in the data analysis was based on two separate project objectives:

a) to predict the amounts of these pollutants from more readily measurable variables (surrogates), and

b) to determine how to control the amounts of pollutants of concern leaving the incinerator.

To reflect these objectives, the independent variables were separated into two groups. The independent variables that were used to generate the prediction models were labelled the monitoring variables, and those that were used to generate the control models were labelled the operating variables.

Multiple regression correlations were generated using anywhere from two to six variables. As required, variables were added in an attempt to improve the models. If the addition of a variable failed to increase the coefficient of determination (r^2) by at least 0.01 over the previous model it was rejected as producing no significant improvement to the fit. The final number of variables used in the "best fit" models were based on the experience and judgement of the reviewers. In a majority of the cases, three

variable models were chosen. In a few cases, two variable models were selected, since additional variables made no significant improvement.

The control model operating variables were chosen which best reflected the three "t's" of combustion - residence time, temperature and turbulence. Control models that included more variables than were necessary to represent the three "t's" were rejected. This resulted in three variable equations being selected for most models and some two variable equations, as mentioned above.

The prediction models employed were divided into two sets:

a) those that included nitrogen oxides, and
b) those that did not.

This division was made because of the uncertainty as to the significance of nitrogen oxides in the equation.

The control models were also divided into two sets:

a) those that used steam rate, and
b) those that used refuse feed rate.

The very high correlation between steam rate and refuse feed rate precluded treating them as independent of one another.

The multiple regression graphs in this section show a straight diagonal line to mark the position of a "perfect fit" between the measured and calculated values. Numbers plotted on the graphs mark the actual values obtained and data points 2 to 15 correspond to the performance test runs PT-02 to PT-15. The closer the numbers approach the diagonal, the stronger the model.

Two parallel lines have been placed on each side of the diagonal of these graphs: one above and one below the "perfect fit" diagonal. These lines are each displaced from the perfect fit by a distance equal to the average of the absolute values of all the residuals. The band formed by these lines is called the residual band and is used to visually represent the r^2 value. The residual band has no statistical significance beyond the purpose of visual comparisons between correlations models. The narrower the residual band, the closer the numbers approach the diagonal and, therefore, the higher the r^2 values and the stronger the model. As more variables are added to a model, the residual band should become narrower; otherwise the model should be rejected.

Accompanying tables with some of the graphs show the progressive increase in r^2 achieved by going from a one-variable model to a two-variable model and then the

three-variable model. The regression coefficients for the best fit model are highlighted in each table and the best fit equations resulting from these regression coefficients are shown at the bottom of each table.

6.4.2 Dioxins.

Prediction model. The prediction model for dioxins that employed nitrogen oxides, carbon monoxide and moisture in the flue gas resulted in one of the highest r^2 values (0.89). This model, as shown in Figure 6.7A, fits evenly and closely around the diagonal line, as indicated by the narrow residual band, with the exception of test point 3 (PT-03). PT-03 is well below the line, indicating that the model predicts a lower dioxin concentration than was actually measured for this run. Despite the effect of this test point on the model, all the other test points fit exceptionally well.

A similar prediction model without the nitrogen oxides data did not fit as tightly to the line, as shown in Figure 6.7B and demonstrated by the wider residual band. PT-03, -04, -07 and -11 fit as poorly as did PT-03 on Figure 6.7A, which would explain the lower r^2 value (0.72). The points form a band centred on the diagonal and the band is of roughly equal width over the full range of dioxin values. This would indicate that the assumption of a linear relationship is correct. As shown in Table 6.8, the models with (6.7A) and without (6.7B) nitrogen oxide employed carbon monoxide as the primary variable.

Control model. The control model for dioxin is shown in Figure 6.7C. This model fits as closely to the line as the nitrogen oxides prediction model, as can be seen by the comparable residual bands. The strong correlations (r^2 of 0.89) obtained with this model suggest that the dioxin emissions can be controlled by appropriate adjustments of the total air flow, primary/secondary ratio, and steam rate.

On all three figures, the test points representing poor operating conditions (3, 4, 14 and 15) are located in the upper right corner of the graph. This is the region of the highest dioxin emissions as well. As anticipated, the poor operating conditions produced higher levels of dioxins.

Additional information pertaining to the relationship between dioxins and the operating and monitoring variables can be found in Table 6.8. From Table 6.8A, it can be shown that an increase in either carbon monoxide, nitrogen oxides or moisture in the flue gas could result in an increase in dioxin emissions. However, in Table 6.8B where nitrogen oxides were omitted, the data suggested that a decrease in lower radiation chamber temperature, or an increase in carbon monoxide and moisture could cause an increase in

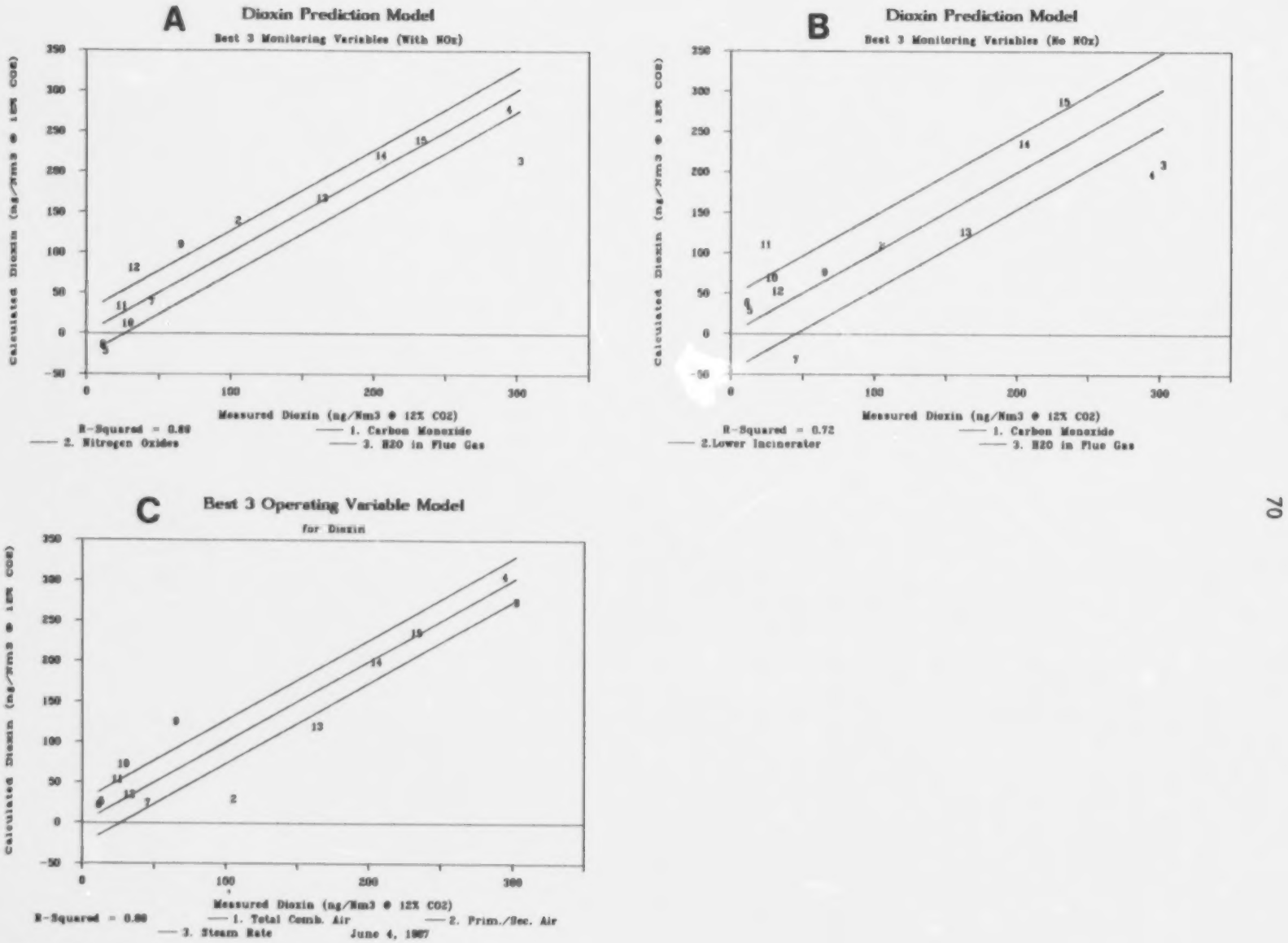


FIGURE 6.7 DIOXIN CORRELATIONS

TABLE 6.8 MULTIPLE REGRESSION ANALYSIS FOR DIOXIN MODELS

DIOXIN (ng/Sm3 @ 12% CO2) PREDICTION MODEL
Best 3 Monitoring Variables (With NOx) **A**

VARIABLE	UNITS	1	2	3	4
R2		0.51	0.88	0.89	0.91
CARBON MONOXIDE	ppm	1.55	1.52	1.58	1.68
NITROGEN OXIDES	ppm		2.93	3.10	2.86
MOISTURE IN THE FLUE GAS	%			8.30	
OXYGEN IN THE FLUE GAS (DRY)	%				-32.9
LOWER INCINERATOR TEMPERATURE	deg C				-0.545
INTERCEPT		22.1	-561	-717	324
C(p)		28.0	2.08	3.38	4.01

Best Fit Prediction Equation
Total PCDD = Carbon Monoxide x 1.58 + Nitrogen Oxides x 3.10 + Moisture in Flue Gas x 8.30 - 717

DIOXIN (ng/Sm3 @ 12% CO2) PREDICTION MODEL
Best 3 Monitoring Variables (no NOx) **B**

VARIABLE	UNITS	1	2	3	4
R2		0.51	0.69	0.72	0.72
CARBON MONOXIDE	ppm	1.55	1.53	1.66	1.66
LOWER INCINERATOR TEMPERATURE	deg C		-0.58	-0.793	-0.815
MOISTURE IN THE FLUE GAS	%			19.4	18.5
OXYGEN IN THE FLUE GAS (DRY)	%				-2.03
INTERCEPT		22.1	577	492	548
C(p)		5.15	2.00	3.00	5.00

Best Fit Prediction Equation
Total PCDD = Carbon Monoxide x 1.66 - Lower Incinerator Temp. x 0.793 + Moisture in Flue Gas x 19.4 + 548

DIOXIN (ng/Sm3 @ 12% CO2) CONTROL MODEL
Best 3 Operating Variables **C**

VARIABLE	UNITS	1	2	3	4
R2		0.77	0.82	0.89	0.89
PRIMARY AIR FLOW	m3/min	0.93			
TOTAL AIR FLOWS	m3/min		0.59	0.69	0.70
PRIMARY/SECONDARY AIR DIST. RATIO			28.60	32.6	30.50
STEAM RATE	Tonnes/hr.			-7.85	-7.67
SECONDARY F/R COMB. AIR DIST. RATIO					-15.70
SECONDARY AIR FLOW	m3/min				
INTERCEPT		-260	-324	-190	-192
C(p)		4.65	3.77	1.54	3.37

Best Fit Control Equation
Total PCDD = Total Air Flows x 0.694 + Primary/Secondary Air Ratio x 32.6 - Steam Rate x 7.67 - 190

dioxin. The control model in Table 6.8C indicates that increasing the total air flow or the primary/secondary air ratio could increase dioxin emissions. These findings suggest that modelling may be an effective means of using both operating and monitoring variables for predicting and eventually controlling dioxin emissions.

6.4.3 Furans.

Prediction model. The prediction model for furans that included nitrogen oxide data resulted in a very high r^2 value (0.90). The variables used in this model are the same three that were used for predicting dioxins -- nitrogen oxides, carbon monoxide and the percent moisture in the flue gas -- and are shown in Figure 6.8 and Table 6.9. As shown in Figure 6.8A, the prediction model produces a close fit to the data, as indicated by the narrow residual band and the even distribution of residuals along the full length of the line.

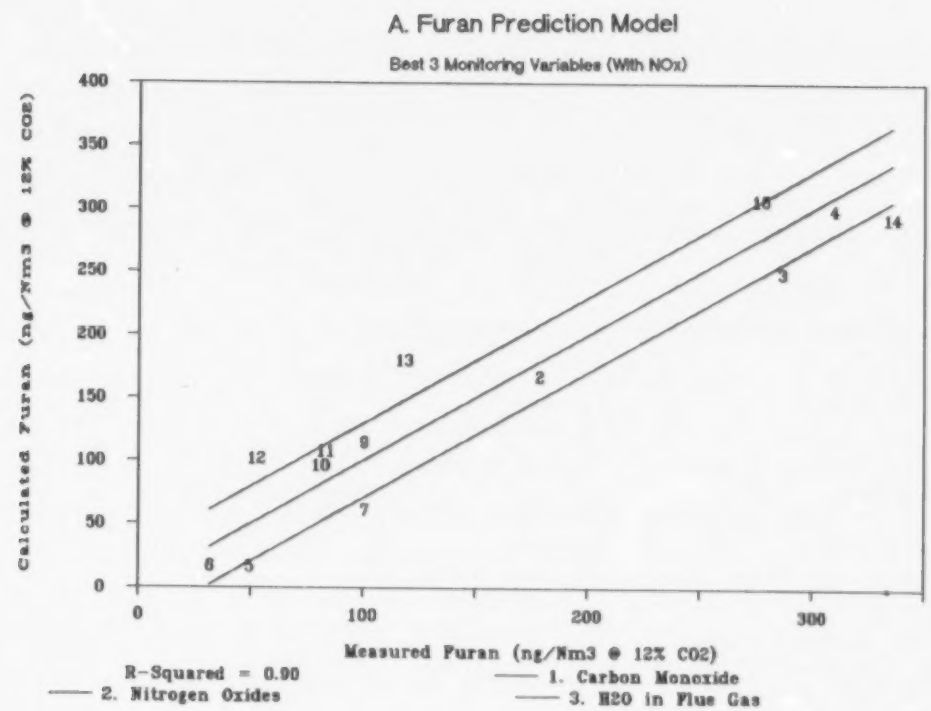
The prediction model for furans generated without nitrogen oxides resulted in a lower r^2 value (0.81) than the model involving nitrogen oxide, but this value is still very good. Only two variables were used in this model, carbon monoxide and lower incinerator temperature. These two variables were also chosen for dioxins when nitrogen oxides were not considered. Although the moisture in the flue gas improved the predictive capability of the dioxin model, the furan model showed an insignificant improvement when this variable was added.

Control model. The control model for furans, as shown in Figure 6.8B, resulted in a high r^2 value (0.84) and used the same three variables that were used to control dioxin. These variables were primary/secondary ratio, total air flow and steam rate.

As with dioxins, the upper right corner of both furan graphs contain all four points representing poor operating conditions. This further confirms the expectation of higher emission levels with poor operating conditions.

6.4.4 Chlorophenols and Chlorobenzenes.

Prediction model. The prediction models for chlorophenol and chlorobenzene involving nitrogen oxides resulted in the best r^2 values (0.86 and 0.87, respectively). The variables used in this model included the same two that were used for predicting dioxins and furans: nitrogen oxides and carbon monoxide. The third variable for chlorophenols was lower radiation chamber temperature, whereas for the chlorobenzenes model it was oxygen. As previously noted for dioxins and furans, the chlorophenol and chlorobenzene models that excluded nitrogen oxides showed a lower correlation than the models that included nitrogen oxides.


A. Furan Prediction Model
Best 3 Monitoring Variables (With NOx)
Calculated Furan (ng/Nm3 @ 12% CO2)
Measured Furan (ng/Nm3 @ 12% CO2)
R-Squared = 0.90
1. Carbon Monoxide
2. Nitrogen Oxides
3. H2O in Flue Gas

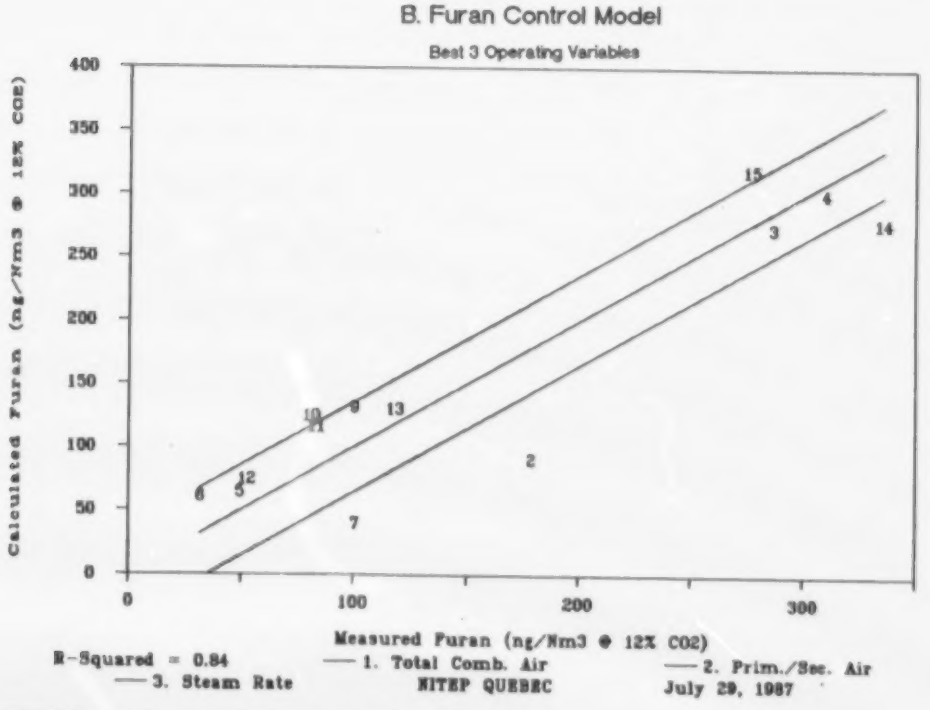


FIGURE 6.8 FURAN CORRELATIONS

TABLE 6.9 MULTIPLE REGRESSION ANALYSIS FOR FURAN MODELS

HITKP-QUEBEC CITY COMBUSTION TEST — MULTIPLE REGRESSION ANALYSIS 02/26/88

FURAN (ng/Sm3 @ 12% CO2) PREDICTION MODEL **A**
Best 3 Monitoring Variables (with NOx)

VARIABLE	UNITS	1	2	3	4
R2		0.61	0.88	0.90	0.90
CARBON MONOXIDE	ppm	1.70	1.68	1.68	1.63
NITROGEN OXIDES	ppm		2.51	1.90	1.93
LOWER INCINERATOR TEMPERATURE	deg C			-0.264	-0.182
MOISTURE IN FLUE GAS	%				-6.66
CONTINUOUS FLUE GAS OXYGEN (DRY)	%				
INTERCEPT		49.7	-450	-76.1	-66.9
C(p)		27.3	4.20	4.33	5.96

Best Fit Prediction Equation
Total PCDF = Carbon Monoxide x 1.68 + Nitrogen Oxides x 1.90 - Lower Incin. Temp. x 0.264 - 76.1

FURAN (ng/Sm3 @ 12% CO2) CONTROL MODEL **B**
Best 3 Operating Variables

VARIABLE	UNITS	1	2	3	4
R2		0.55	0.74	0.84	0.86
PRIMARY AIR FLOW	m3/min	0.79			-0.724
PRIMARY/SECONDARY AIR DIST. RATIO			63.80	39.9	58.8
SECONDARY AIR FLOW	m3/min		1.12		
TOTAL AIR FLOWS	m3/min			0.591	1.04
STEAM RATE	Tonnes/hr.			-10.3	-10.20
SECONDARY F/R COMB. AIR DIST. RATIO					
INTERCEPT		-166	-261	-39.4	-78.6
C(p)		14.1	6.47	3.30	4.01

Best Fit Control Equation
Total PCDF = Total Air Flows x 0.591 + Primary/Secondary Air Ratio x 39.9 - Steam Rate x 10.3 - 39.4

Control model. The control models for chlorophenol and chlorobenzene resulted in lower but still strong r^2 values (0.77 and 0.82, respectively) using two of the same three variables that were used in the dioxin control model. These variables were primary/secondary ratio and total air flow. The third variable was the same for chlorophenols (steam rate) but the secondary front/rear air ratio was chosen to "fine tune" the model for chlorobenzenes.

6.4.5 Polycyclic Aromatic Hydrocarbons and Polychlorinated Biphenyls.

Prediction models. Polycyclic aromatic hydrocarbons and polychlorinated biphenyls showed a number of similarities in their regression models. Both of these organics have distinctly different models from those of dioxins, furans, chlorophenols, or chlorobenzenes. The only characteristic that these two organics have in common with the others is that the best prediction models were those involving nitrogen oxides. Unlike the other organics models, these models did not use carbon monoxide as a variable. Both prediction models used nitrogen oxides, oxygen and lower radiation chamber temperature and had relatively high r^2 values (0.73 and 0.62 respectively). However, despite the quite respectable r^2 values, these models have inadequate predictive powers because the test points for both good and poor operating conditions are randomly scattered over the graph.

The prediction models excluding nitrogen oxides both had relatively low r^2 values (0.41 and 0.28, respectively); both used lower radiation chamber temperature, oxygen and carbon monoxide as variables. These values were considered too low and these models were rejected. No suitable surrogate models were found for polycyclic aromatic hydrocarbons or polychlorinated biphenyls.

Control models. The control model for polycyclic aromatic hydrocarbons had a reasonable r^2 value (0.63) while the control model for polychlorinated biphenyls had a very low r^2 value (0.27). As in the case of the prediction models, where data for both good and poor operating conditions were randomly scattered over the graph, these control models were judged inadequate and were rejected.

7 ASH CHARACTERIZATION

Recently, concern has been expressed by government agencies and environmental groups over the handling and disposal practices for residues from municipal solid waste incinerators. To address these concerns and to assist in the development of guidelines for ash management stategies, ash samples from the QUC incinerator were subjected to a battery of characterization and leachability tests. This chapter provides a summary of the results from the experimental program conducted on representative sub-samples of bottom ash, boiler/economizer fly ash and electrostatic precipitator fly ash. The ashes were selected from one test run from each of the five performance tests detailed in Chapter 5.

7.1 Organics Leachability

The ashes were analyzed for various trace organic compounds of environmental concern, including dioxins (PCDD), furans (PCDF), polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCB), chlorophenols (CP) and chlorobenzenes (CB). The average concentrations in each type of ash for the five performance test runs are given in Table 7.1. With the exception of PAHs, concentrations of organic compounds increased from bottom ash through to precipitator ash, as outlined in Section 5. This was due to the volatile nature of most organic compounds and the larger sorptive surface area of the smaller particles of precipitator ash.

The leachability of the trace organic compounds from the ashes under non-agressive leaching conditions was determined using a distilled water batch leach test. This test involves slowly mixing the ash with distilled water at a 20:1 liquid-to-solid ratio for 18 hours, then separating the liquid phase for analyses. Test results are summarized in Table 7.2, which indicates that no dioxins, furans, or polychlorinated biphenyls were leached from the ashes. Trace quantities, below 0.3 ppb of CP, below 0.08 ppb of PAH and below 0.03 ppb of CB were detected in the leachates. Since chlorobenzenes and PAHs are insoluble in water, it is speculated that these compounds were bound to ultra-fine particles, which passed through the glass fibre filters used during leachate sample processing and remained in suspension in the leachate.

While these results indicate that organic contaminant mobility is limited when the ashes have been in contact with water, this test does not account for the potential leachability of organic contaminants under landfill conditions. The activity of microbes,

TABLE 7.1 AVERAGE TRACE ORGANIC CONCENTRATIONS IN ASHES (leachability test samples)

	Concentration (ng/g)		
Organic Contaminant	Bottom Ash	Boiler/ Economizer Ash	Precipitator Ash
PCDD	0.03	58.6	718
PCDF	ND	43.2	244
PAH	388	71.6	239
CP	13.7	124	2300
CB	5.25	526	1510
PCB	ND	ND	5.8

ND = not detected

TABLE 7.2 AVERAGE ORGANIC CONTAMINANT CONCENTRATIONS IN LEACHATE

	Concentration (ppb)		
Organic Contaminant	Bottom Ash	Boiler/ Economizer Ash	Precipitator Ash
Dioxins	ND	ND	ND
Furans	ND	ND	ND
PAH	0.08	0.02	0.01
Chlorophenol	0.14	0.24	0.14
Chlorobenzene	0.01	0.03	0.02
PCB	ND	ND	ND

ND = Not detected.

the generation of organic acids, the presence of solvents or the migration of colloidal particles, may dramatically alter the mobility of some of these compounds. Organic contaminant-specific leach tests are being developed to provide the information necessary to evaluate organic contaminant mobility under conditions more representative of landfill disposal.

7.2 Metals Leachability

The ashes used for the leachability tests were also analyzed for boron, cadmium, chromium, cobalt, copper, lead, nickel and zinc prior to undergoing leaching tests. The average metal concentrations in the ashes are shown in Figure 7.1. Generally, the results are similar to those from previous NITEP studies, in that relatively low to moderate concentrations of boron, cadmium, chromium, cobalt, copper and nickel, and very high concentrations of lead and zinc were measured in all three types of ash. The distribution of metals among the three types of ash is dependent on the volatility of the metal concerned. Generally, the more volatile metals, such as cadmium, lead and zinc were found in higher concentrations in the precipitator ashes, while less volatile metals such as chromium, cobalt and nickel were measured in higher concentrations in the bottom ashes.

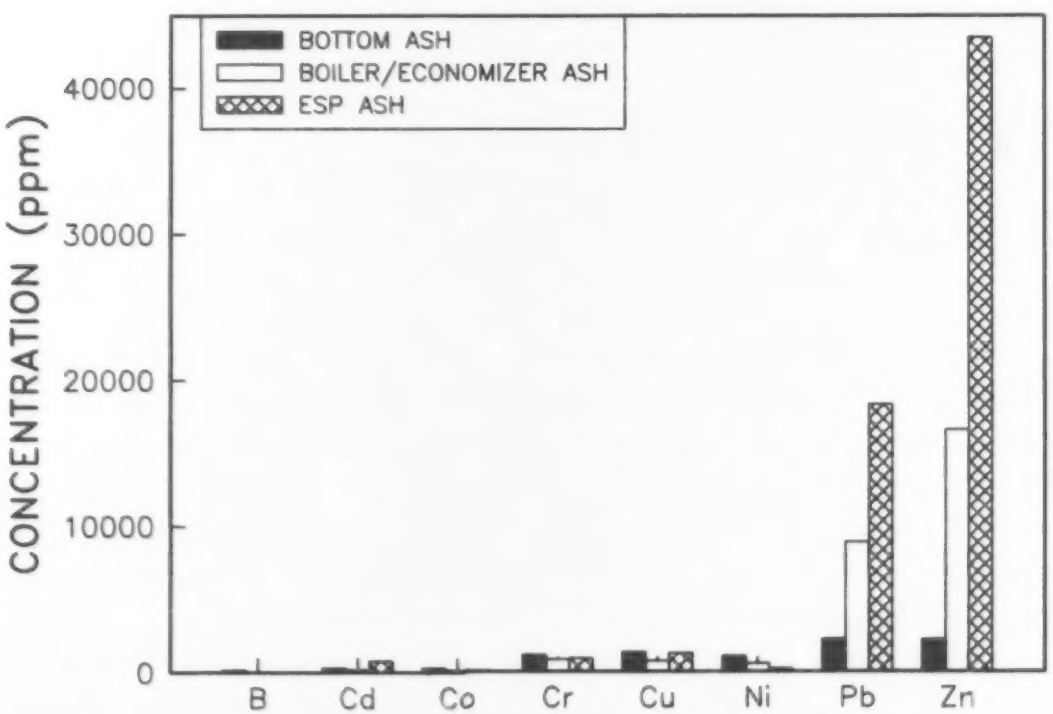


FIGURE 7.1 AVERAGE HEAVY METAL CONCENTRATIONS IN ASHES

The leachability of metals from the ashes was determined by three different leach tests: the multiple sequential batch leach procedure (MSBLP), a sequential

chemical extraction procedure (SCE) and the Government of Ontario Regulation 309 Leach Test (11,12,13). Table 7.3 provides a brief description of the tests.

TABLE 7.3 SUMMARY OF THE LEACHING TESTS

Description	Interpretation
Multiple Sequential Batch Leaching Procedure	
Distilled water leach at 20:1 liquid-to-solid ratio, mixed slowly for 18 hours.	Use results to help determine metal speciation and fraction potentially available for leaching with water.
Reclaim solids and expose to fresh leaching medium. Repeat for 5 cycles.	
Sequential Chemical Extraction Procedure	
Fraction A - Digest ground sample with 1 M LiCl/CsCl in 60% CH_3OH - residue to B.	Ion exchangeable fraction. Considered immediately available for leaching.
Fraction B - 1 M CH_3COONa with Acetic Acid - pH 5 - residue to C.	Surface oxide and carbonate bound ions. Considered potentially available for leaching under acidic leaching conditions.
Fraction C - 1 M $NH_2OH \cdot HCl$ in 25% Acetic Acid - residue to D.	Iron and manganese bound metal ions. Considered potentially available for leaching under the more aggressive conditions of an older landfill.
Fraction D - Nitric Acid with Peroxide Heat → add CH_3OONH_4 in 20% Nitric Acid - residue to E.	Sulphide and organic matter bound metal ions. Considered unavailable for leaching under normal landfill conditions.
Fraction E - Aqua regia/HF with peroxide and HCl.	Residual metal ions. Considered unavailable for leaching.
Government of Ontario Regulation 309 Leach Test (similar to the U.S. Environmental Protection Agency EP TOX test)	
20:1 liquid-to-solid ratio leach with max. volume of 0.5 N Acetic acid to maintain pH at < = 5.	Results compared against 100 times Ontario's Drinking Water Quality Objectives.

Both types of fly ash were found to be highly soluble in water, with almost 40% of the precipitator ash and 25% of the boiler/economizer ash being dissolved during the five cycles of the MSBLP. Conversely, the bottom ash was much less soluble with only about 4% of the material being dissolved over the same period (See Figure 7.2). The high solubility of the precipitator ash was due to the pH of the ash, the high concentrations of readily soluble salts, and the small size of the particles. Figure 7.3 illustrates the effect of leachate pH on the solubility of cadmium and zinc from the precipitator ashes. The lower solubility of the bottom and boiler/economizer ashes was attributed to the alkaline pH of the ashes and the presence of relatively insoluble silicates and oxides.

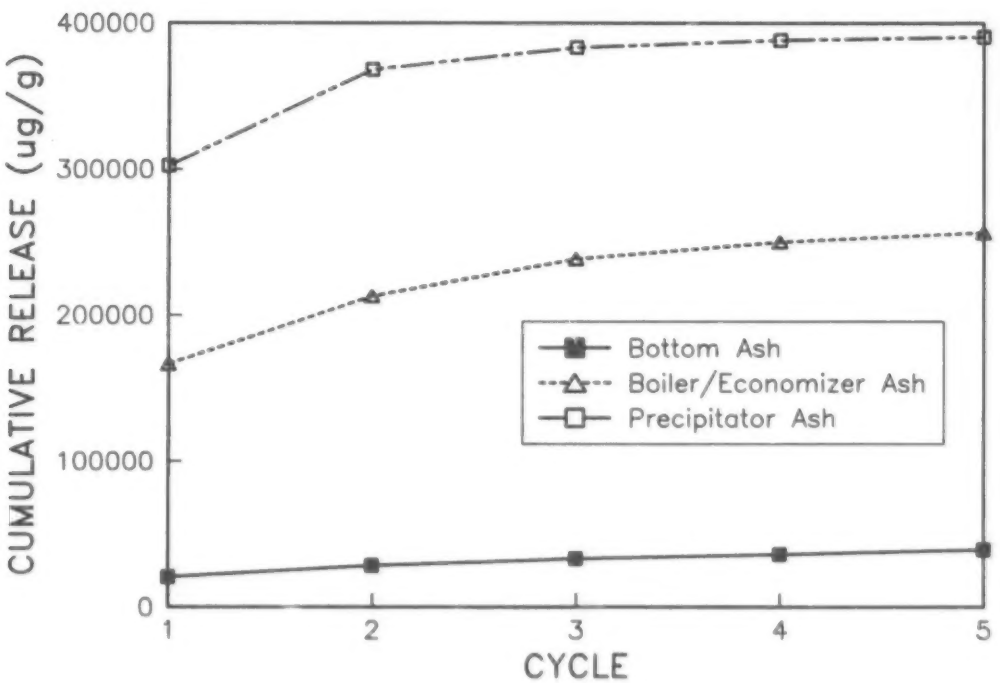


FIGURE 7.2 AVERAGE CUMULATIVE TOTAL DISSOLVED SOLIDS RELEASED DURING MULTIPLE SEQUENTIAL BATCH LEACHING

This summary provides the results for the three most leachable metals from the SCE analyses, namely, cadmium, lead, and zinc. Results for the remaining metals may be obtained from Environment Canada. Figure 7.4 shows that about half of the

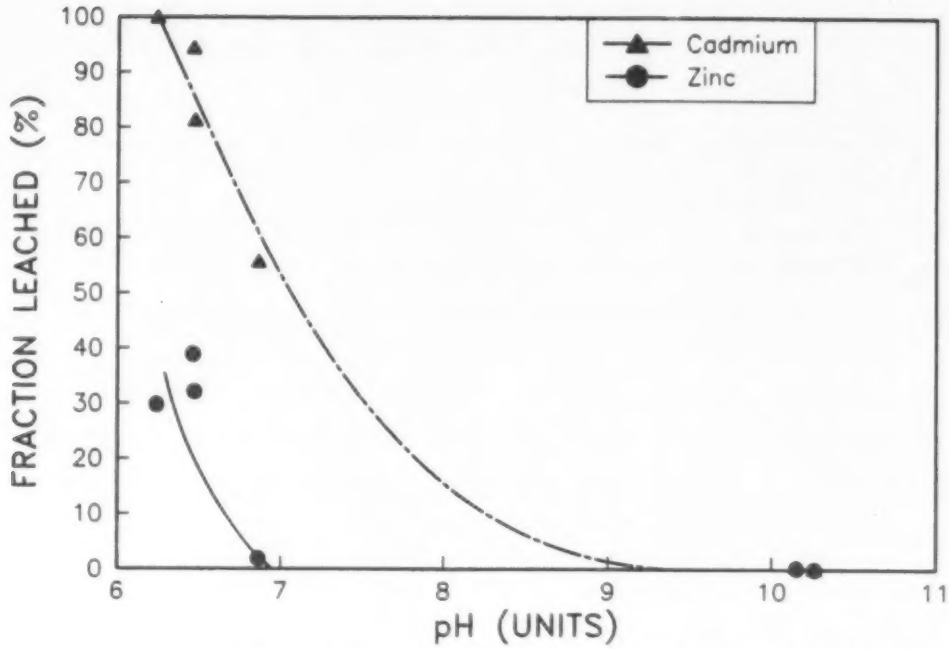


FIGURE 7.3 EFFECT OF pH ON SOLUBILITY OF CADMIUM AND ZINC IN PRECIPITATOR ASH

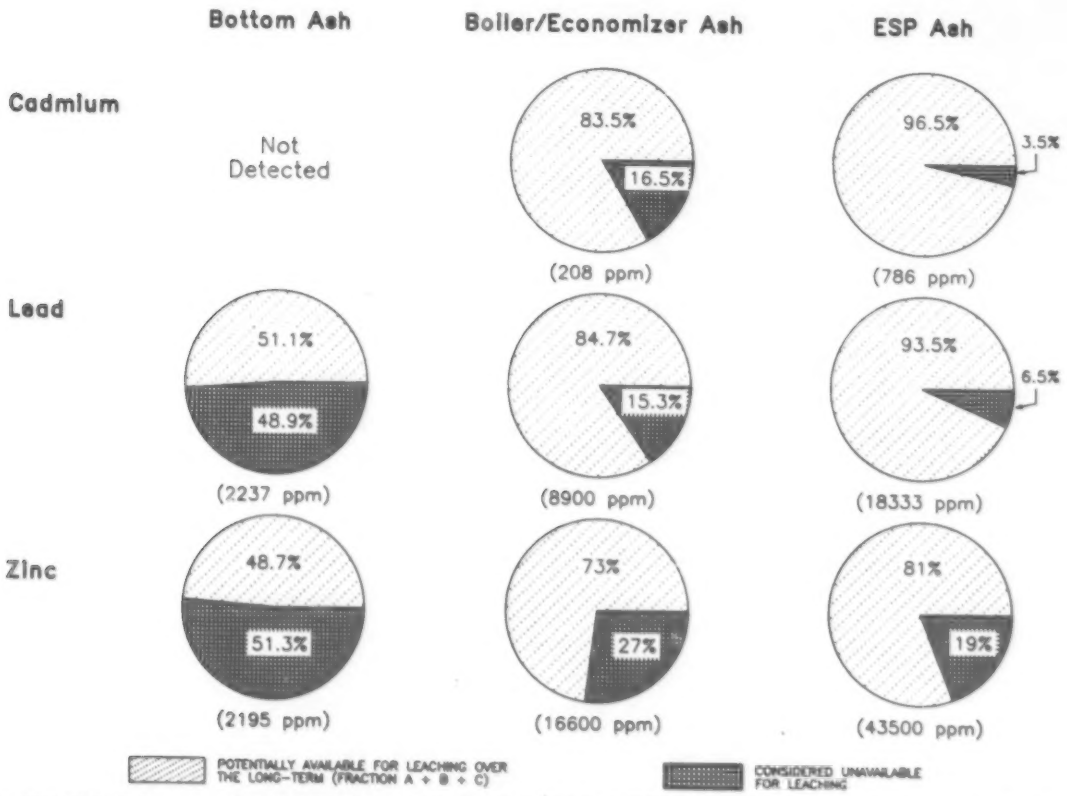


FIGURE 7.4 LONG-TERM LEACHABLE FRACTION RESULTS FROM THE SCE ANALYSES

TABLE 7.4 ONTARIO REGULATION 309 LEACH TEST RESULTS FOR BOILER/ ECONOMIZER AND PRECIPITATOR FLY ASHES

Parameters	Drinking Water Objectives x 100 (ppm)	Average Leachate Concentrations (ppm)	
		Boiler/Economizer Fly Ash	Precipitator Fly Ash
Cadmium	0.5	6.84	28.3
Lead	5.0	40.0	35.9
Zinc	500	363	1590

relatively low levels of lead and zinc present in the bottom ash were available for leaching over the long-term. Conversely, substantially greater quantities of cadmium, lead and zinc were potentially available for leaching from the boiler/economizer and electrostatic precipitator fly ashes under the same conditions. The reason for this difference was that the fly ashes contained high concentrations of readily soluble metal salts, especially cadmium and zinc, whereas the bottom ash consisted mainly of relatively insoluble metal oxides and silicates.

The results of the Government of Ontario Regulation 309 Leach Test (Table 7.4) indicated that, with the exception of zinc in the boiler/economizer ash leachate, cadmium, lead and zinc concentrations in fly ash leachates exceeded the regulatory guideline levels by at least a factor of 3, and in the case of cadmium, by a factor of 57. As a result the fly ashes would be considered hazardous under the Ontario regulation.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Performance Test Conclusions

8.1.1 Test Program Conclusions

1) Emissions of polychlorinated dibenzo-p-dioxins (19 ng/Sm^3) and polychlorinated dibenzo furans (44 ng/Sm^3) during good operating conditions at the design burning rate were within the lower range of values reported in published literature (14) for mass burning incinerators equipped with electrostatic precipitators.
2) Test results indicated that the design can have a significant impact on the levels of dioxin (PCDD) and furan (PCDF) emissions. Emissions of dioxins and furans were much lower for the modified unit than emissions obtained by the Quebec provincial government from the unmodified unit in December 1985 (i.e., on average, 1985 ng/Sm^3 PCDD and, 476 ng/Sm^3 PCDF).
3) Test data indicated that the manner in which the incinerator is operated can influence dioxin and furan emission levels. PCDD/PCDF emissions were significantly higher during poor operating conditions at the design burning rate, ranging from 219 to 299 ng/Sm^3 (PCDD) and 298 to 306 ng/Sm^3 (PCDF).
4) The carbon monoxide concentration in the flue gas provided a good indication of system operation. Operating conditions that generated low CO emissions (less than 50 ppm) and maintained steady steam production resulted in low concentrations of trace organic emissions.
5) Hi-Vol sampling at the unmodified unit and the modified unit showed an almost 20-fold lower level of particulate emissions from the modified unit. This confirmed that design and operation have a significant impact on particulate emissions as well as on PCDD/PCDF emissions. Furthermore, comparison of particulate test results prior to 1984 (unmodified design) with particulate emissions from the modified unit showed a lower but significant reduction.
6) Analyses of multiple samples of refuse indicated that refuse composition varied considerably over time. Multiple analyses of each collected sample indicated that the analytical repeatability for most compounds was acceptable.
7) Hydrogen chloride (HCl) emissions were between 366 and 565 ppm which are typical of similar North American facilities (14) without acid gas removal.
8) Close examination of the particle size distribution results showed no relationship between distribution and the operating mode.

9) The concentrations of organics and most metals in the ashes showed that precipitator ash concentrations were consistently greater than boiler ash concentrations, which in turn were greater than incinerator ash concentrations.

10) Organic contaminant mobility was found to be limited when ashes were contacted with water in a batch leach test. Results indicated that no dioxins, furans, or polychlorinated biphenyls were leached from the ashes. Trace quantities of chlorophenols, polycyclic aromatic hydrocarbons, and chlorobenzenes were detected in the leachates.

11) Results from multiple sequential batch leaching tests indicated that fly ashes are highly soluble in water, but bottom ash is only sightly soluble.

12) Significant quantities of cadmium, lead and zinc are present and leaching from fly ashes (both/economizer and precipitator) could occur over the long term.

8.1.2 Simple Regression. Over 20 000 simple linear correlations were examined. The following summarizes the most important of these.

1) Dioxin and furan exhaust emissions showed strong correlations with the following parameters:

   a. carbon monoxide emissions;
   b. particulate emissions;
   c. exhaust gas flow and primary air flow;
   d. chlorobenzene (CB) and chlorophenol (CP) emissions; and
   d. copper exhaust emissions.

2) No correlation was found between dioxin or furan emissions and:

   a. dioxin and furan concentrations in the refuse; and
   b. polycyclic aromatic hydrocarbon and polychlorinated biphenyl emissions.

3) Particulate emissions correlated with the following:

   a. carbon monoxide emissions;
   b. exhaust gas flow and primary air flow;
   c. some of the trace organics emissions, namely dioxin, furan, and chlorobenzenes; and
   d. most of the priority metal emissions, such as cadmium, copper and lead.

4) Emissions of selected metals correlated well with chlorobenzene, chlorophenol, dioxin, and furan emissions. It is believed that the reason for the correlations

between the priority metals and trace organics is that these contaminants are generally associated with the particulate material and will consistently vary up or down depending on particulate loads. No correlations were found between trace organics and mercury emissions.

5) Lower radiation chamber temperature correlated well with combustion parameters such as oxygen and carbon dioxide concentrations. Oxygen concentrations correlated inversely with process temperatures while carbon dioxide correlated directly with process temperatures.

6) Primary air flow correlated with the following:

   a. particulate concentration at the precipitator inlet;
   b. trace organic emissions (dioxins, furans, chlorophenols, chlorobenzene); and
   c. metal emissions at the precipitator inlet (cadmium, copper, nickel, antimony, chromium, and zinc).

7) Secondary air flow correlated poorly with the trace organics, particulate, and metal emissions.

8) Although strong correlations occurred between carbon monoxide emissions and dioxin, furan, chlorobenzene, and chlorophenol emissions, no correlations were observed when carbon monoxide was compared with primary air and flue gas flow.

9) Excess air correlated well with all process parameters but did not correlate with trace organic and metal emissions.

10) Strong correlations were found between precipitator ash metal concentrations of chromium, copper, and nickel and the emission rates of dioxins, furans, chlorobenzenes and chlorophenols. These correlations suggest that emissions of trace organics may be predicted by monitoring the rate and concentration of metals in the precipitator ash.

11) Poor correlations were found between the following:

   a. combustion chamber temperatures and nitrogen oxide emissions;
   b. hydrogen chloride emissions and chlorine concentrations in the refuse; and
   c. hydrogen chloride emissions and trace organic emissions.

8.1.3 Multiple Regression. In general, simple regression models employing only one variable were considered to be a good first-order screening for either controlling or predicting trace organic emissions. Accordingly, multiple regression analyses were undertaken. Key results are presented below.

1) Multiple linear regression analysis of the Quebec test data produced models to predict and to control trace organic emissions. Coefficients of determination, which are indicators of the model's strength, ranged from 0.74 to 0.90 for the best fit multiple linear regression models.

2) The prediction models that best characterized trace organic emissions of dioxins, furans, chlorobenzenes and chlorophenols used two or three of the following monitoring parameters:

   a. carbon monoxide,
   b. nitrogen oxides,
   c. oxygen,
   d. water in flue gas, and
   e. lower radiation chamber temperature.

3) The best control models to minimize trace organic emissions used three of the following operational settings:

   a. total air flow,
   b. primary/secondary air ratio,
   c. steam rate or refuse rate, and
   d. secondary air front/rear ratio.

4) Carbon monoxide was determined to be the best single surrogate in the one-variable (simple) prediction model for most of the trace organics, with the exception of polycyclic aromatic hydrocarbons and polychlorinated biphenyls.

5) Although nitrogen oxide was the best second variable to improve the prediction capabilities of the models, its significance is not clearly understood at this time.

6) If nitrogen oxide were excluded from the prediction models, the next most important variable would be lower radiation chamber temperature, followed by either oxygen or moisture in the flue gas.

7) Primary air flow was the most influential operational setting for the one-variable control models for dioxins, furans, chlorobenzenes and chlorophenols.

8) The polychlorinated biphenyl and polycyclic aromatic hydrocarbon models examined contained either a relatively low coefficient of determination value or the data scatter implied a poor predictive model.

9) The models developed for dioxins, furans, chlorobenzenes and chlorophenols are consistent with the finding that poor incinerator operating conditions resulted in higher emission concentrations.

8.2 Combustion and Operational Conclusions

1) Emission concentrations were relatively low under good operating conditions at the three steam rates tested (i.e., 20, 28, and 32 t/h - 'low', 'design', and 'high', respectively). Good operation was defined as:

   a. maintaining relatively low and steady carbon monoxide concentrations;
   b. maintaining a reasonable split of primary to secondary air;
   c. maintaining a proper burning bed depth and profile on all three grate zones;
   d. eliminating slugs of refuse by setting up the control system for obtaining the appropriate grate speeds;
   e. avoiding slag build-up on the refractory walls which reduced the effective grate area;
   f. minimizing flame impingement on the boiler inlet tubes; and
   g. maintaining a good primary air distribution to all the grates.

2) Attempts to improve ash quality (i.e., no visible burnables) using high primary air flow and low secondary air flow significantly increased emissions.

3) Based on visual observations, when the percentage of total primary (underfire) air to the front burning grate was disproportionately high, particle lift-off occurred and the amount of glowing particles in the upper chamber increased. In addition, as the quantity of air to this zone was increased, flame impingement on the boiler tubes increased.

4) Low upper radiation chamber temperatures and high excess air levels occurred when the percentage of total underfire air to the finishing grate was increased above normal. This was due to the lack of burnables on these grate areas. In response, combustion air to the front finishing grate zones was diminished, reducing the burning rate in this area. As a result, the grate bed depth deepened, and ash quality declined (i.e., burnables discharged into the quench tank increased).

5) Slag formation on the lower furnace walls appeared to be caused by excessively high primary air flows. This condition usually occurred when the "top" or upper furnace radiation chamber temperatures were low. The excessively high primary air flows

increased particulate lift-off and locally increased the temperature in the lower furnace zones, which in turn promoted slagging on the walls near the burning grate.

6) Refuse bed depth on the grate indirectly establishes the amount of primary air required. For example, for a specific steam requirement, a thick refuse bed requires less primary air to supply the energy necessary to provide the steam demand. With the increased refuse bed depth and less primary air, combustion is incomplete, and the amount of unburned material in the ash increases. Refuse bed depth is therefore a significant control parameter for efficiency, emissions, and ash quality.

7) Rapid grate speed changes increased short-term carbon monoxide excursions. Under automatic control, sudden increases in grate speed occasionally occurred when steam demand fell.

8) Based on visual observations of the ash quality, manual control of the finishing grate speed provided better ash quality (fewer burnables in the ash) than automatic speed control.

8.3 Recommendations

1) Additional statistical analysis of non-linear relationships for the NITEP Quebec data is suggested to possibly develop additional models and obtain a better understanding of interrelationships between emissions and process parameters. Specifically, further study of the organic data may provide insight into the mechanisms of organic formation and destruction, facilitating the development of standard operating practices to greatly reduce emissions.

2) Further studies should be carried out to attain a better understanding of the interrelationship between carbon monoxide, combustion temperatures, primary air flows, and air distributions, to facilitate the development of guidelines for municipal waste mass-burning incinerators.

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APPENDIX

SYMBOLS, ABBREVIATIONS AND HOMOLOGUES OF POLYCHLORINATED DIBENZODIOXINS AND DIBENZO FURANS

APPENDIX

SYMBOLS AND ABBREVIATIONS

SI Prefixes

Prefix	Symbol	Multiplication Factor	Exponent
mega	M	1 000 000	= 10^6
kilo	k	1 000	= 10^3
hecto	h	100	= 10^2
deca	da	10	= 10^1
unit	-	1	= 10^0
deci	d	0.1	= 10^{-1}
centi	c	0.001	= 10^{-2}
milli	m	0.001	= 10^{-3}
micro	μ	0.000 001	= 10^{-6}
nano	n	0.000 000 001	= 10^{-9}
pico	p	0.000 000 000 001	= 10^{-12}

Units

Symbol	Unit	Comments
Mass/Weight		
g	gram	-
tonne	metric tonne	1 tonne = 1 Mg
lb	pound	1 pound = 453.592 g
Length		
m	metre	-
ft	foot	1 ft = 0.3048 m
Volume		
L	litre	-
m^3	cubic metre	1 m^3 = 1000 L
Nm^3	normal cubic metre	at standard conditions 25°C, 101.325 kPa
cm^3	cubic centimetre	
ft^3	cubic foot	1 ft^3 = 0.02832 m^3

SYMBOLS AND ABBREVIATIONS (Cont'd)

Units (cont'd)

Symbol	Unit	Comments
Time		
s	second	-
m (min)	minute	1 min = 60 s
h (h)	hour	1 h = 3600 s
Temperature		
°C	degree Celsius	-
°F	degree Farenheit	-
Pressure		
bar	bar	-
Pa	Pascal	1 Pa = 10^{-5} bar
Acronyms		
ASTM	American Society for Testing and Materials	
NITEP	National Incinerator Testing and Evaluation Program	
EPA	Environmental Protection Agency	United States of America
ASME	American Society of Mechanical Engineers	
Sampling and Analytical Terminology		
XAD-2	Amberlite Resin used to absorb organics	
GC	Gas Chromatography	
MS	Mass Spectrometry	
ECD	Electron Capture Detector	
MID	Multiple Ion Detection	
MM5	Modified Method 5	
CT	Characterization Test	
PT	Performance Test	
QA/QC	Quality Assurance/Quality Control	

SYMBOLS AND ABBREVIATIONS (Cont'd)

Compounds

PCB	Polychlorinated Biphenyls
PAH	Polycyclic Aromatic Hydrocarbons
THC	Total Hydrocarbons
TOX	Total Organic Halides
CP	Chlorophenols
CB	Chlorobenzenes
CO	Carbon Monoxide
CO_2	Carbon Dioxide
O_2	Oxygen
SO_2	Sulphur Dioxide
HCl	Hydrogen Chloride
TSP	Total Suspended Particulate or Particulate Matter
NaOH	Sodium Hydroxide
$KMnO_4$	Potassium Permanganate
H_2O	Water
H_2SO_4	Sulphuric Acid
HNO_3	Nitric Acid
Na_2SO_4	Sodium Sulphate
$HClO_4$	Perchloric Acid
$Ca(OH)_2$	Calcium Hydroxide

Metals

Cd	Cadmium
Be	Beryllium
Mo	Molybdenum
Ca	Calcium
V	Vanadium
Al	Aluminum
Mg	Magnesium
Ba	Barium
K	Potassium
Na	Sodium

SYMBOLS AND ABBREVIATIONS (Cont'd)

Metals (Cont'd)

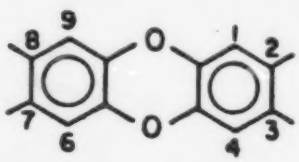
Zn	Zinc
Mn	Manganese
Co	Cobalt
Cu	Copper
Ag	Silver
Fe	Iron
Pb	Lead
Cr	Chromium
Ni	Nickel
Si	Silicon
Ti	Titanium
B	Boron
P	Phosphorus
Hg	Mercury
As	Arsenic
Sb	Antimony
Bi	Bismuth
Se	Selenium
Te	Tellerium
Sn	Tin

Miscellaneous

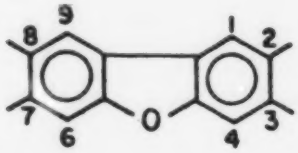
ND	Not Detected
ppm	part per million
°	Degree (angle or temperature)
±	plus or minus
<	less than
>	greater than
ID	Induced Draft (fan)

Polychlorinated Dibenzodioxins and Dibenzofurans

Polychlorinated dibenzodioxins* (PCDDs) are a family of compounds consisting of two benzene rings joined by two oxygen atoms and having from one to eight chlorine atoms attached around the rings (see figure). There are 75 chlorinated dioxins which differ in the positions or number of chlorine atoms. The tetrachlorinated dibenzodioxins (TCDDs) are the 22 different dioxins (isomers) having four chlorine atoms. The isomer known as 2,3,7,8-TCDD has chlorine atoms at the locations numbered 2,3,7 and 8. The polychlorinated dibenzofurans (PCDFs) are a very similar family of compounds differing in that only one of the bonds between the benzene rings contains an oxygen atom. The nomenclature for the chlorinated dibenzofurans is completely analogous to that for the dibenzodioxins.



Polychlorinated Dibenzodioxins
(PCDDs)



Polychlorinated Dibenzofurans
(PCDFs)

Polychlorinated dibenzo-ρ-dioxin homologues:

T4CDD	Tetrachlorodibenzo-ρ-dioxin
P5CDD	Pentachlorodibenzo-ρ-dioxin
H6CDD	Hexachlorodibenzo-ρ-dioxin
H7CDD	Heptachlorodibenzo-ρ-dioxin
O8CDD	Octachlorodibenzo-ρ-dioxin

Polychlorinated dibenzofuran homologues:

T4CDF	Tetrachlorodibenzofuran
P5CDF	Pentachlorodibenzofuran
H6CDF	Hexachlorodibenzofuran
H7CDF	Heptachlorodibenzofuran
O8CDF	Octachlorodibenzofuran

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* The full chemical name is polychlorinated dibenzo-*para*-dioxins or polychlorinated dibenzo-ρ-dioxin.